

FINAL REPORT

Exploration of Advanced Probabilistic and Stochastic Design Methods

(Contract Number NAG-1-2235)

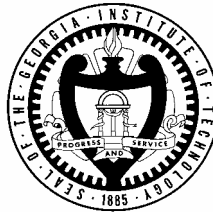
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Executive Summary

The primary objective of the three year research effort was to explore advanced, non-deterministic aerospace system design methods that may have relevance to designers and analysts. The research pursued emerging areas in design methodology and leverage current fundamental research in the area of design decision-making, probabilistic modeling, and optimization. The specific focus of the three year investigation was oriented toward methods to identify and analyze emerging aircraft technologies in a consistent and complete manner, and to explore means to make optimal decisions based on this knowledge in a probabilistic environment.

The research efforts were classified into two main areas. First, Task A of the grant has had the objective of conducting research into the relative merits of possible approaches that account for both multiple criteria and uncertainty in design decision-making. In particular, in the final year of research, the focus was on the comparison and contrasting between three methods researched. Specifically, these three are the Joint Probabilistic Decision-Making (JPDM) technique, Physical Programming, and Dempster-Shafer (D-S) theory.

The next element of the research, as contained in Task B, was focused upon exploration of the Technology Identification, Evaluation, and Selection (TIES) methodology developed at ASDL, especially with regards to identification of research needs in the baseline method through implementation exercises. The end result of Task B was the documentation of the evolution of the method with time and a technology transfer to the sponsor regarding the method, such that an initial capability for execution could be obtained by the sponsor. Specifically, the results of year 3 efforts were the creation of a detailed tutorial for implementing the TIES method. Within the tutorial package, templates and detailed examples were created for learning and understanding the details of each step.

For both research tasks, sample files and tutorials are attached in electronic form with the enclosed CD.

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Introduction

The primary objective of the proposed research is to explore advanced, non-deterministic aerospace system design methods that may have relevance to designers and analysts. The research pursues emerging areas in design methodology and leverage current fundamental research in the area of design decision-making, probabilistic modeling, and optimization. The specific focus of the proposed investigation is oriented toward methods to identify and analyze emerging aircraft technologies in a consistent and complete manner, and to explore means to make optimal decisions based on this knowledge in a probabilistic environment.

The objective in Task A is to arrive at formulations that allow for an n -dimensional examination of a probabilistic objective function space. Such an ability is critical for decision-makers who must allocate resources in the presence of uncertainty. Task B is focused upon exploration of the Technology Identification, Evaluation, and Selection (TIES) methodology developed at ASDL, especially with regards to identification of research needs in the baseline method through implementation exercises.

Task A: Review and Assessment for Approaches to Multi-criteria Optimization under Uncertainty

Design is a decision making process focused upon determining, ultimately, preferred sets of design parameters. Among the decision-making techniques, traditional single criterion approaches fail to account for many real world systems that have multiple (possibly conflicting) criteria. Fortunately, there has been a growing number of multi-criteria approaches. However, many of these operate on deterministic information for the system and environment, and such information is not typically truly known with confidence at the conceptual or preliminary phases. In a typical case, then, assumptions are made and the decision-making process proceeds. This exposes the decision to risk as a result of unaccounted uncertainty in assumptions. Moreover, the use of the new technologies within a design problem adds additional technical and program uncertainty to the design process due to readiness or availability issues. Thus, the present research task, Task A of the grant, has had the objective of conducting research into the relative merits of possible approaches that account for both multiple criteria and uncertainty in design decision-making. In particular, in the final year of research for which this document represents a reporting, the focus was on the comparison and contrasting between three methods researched.

The remainder of this report is structured as follows. First, a review of the three techniques studied will be presented, including mathematical formulation and an assessment of strengths and weaknesses. These three are the Joint Probabilistic Decision-Making (JPDM) technique, Physical Programming, and Dempster-Shafer (D-S) theory. The JPDM and D-S were described extensively in the Year 2 progress report through two P.h.D. theses that were completed. Following the review, a concluding summary is offered that collects the pertinent information on each technique and presents it in the form of recommendations for use depending on a designer's particular problem characteristics. Finally, an appendix is included that contains code, run-time instructions, and an example of executing the JPDM method. It is hoped that this appendix can facilitate the immediate use of the technology by NASA researchers. The doctoral thesis that was the culmination of JPDM research, delivered to NASA under this grant last year, can be referred to for answers to detailed questions.

1. Joint Probability Decision Making (JPDM) Technique

The Joint Probabilistic Decision Making (JPDM) technique, which was developed at Aerospace System Design Laboratory (ASDL) and reported to NASA in last year's report under this grant, incorporates a multi-criteria and a probabilistic approach to systems design. Its essential function is to estimate the probability of satisfying the criteria concurrently under uncertainty. This is done primarily through the construction of joint probability functions, which result when multiple random variables, each having their own marginal distribution, are involved. In JPDM, the criteria themselves are the random variables and so the joint distribution sought includes all of them.

There are two models in the JPDM technique: the Joint Probability Model (JPM) and Empirical Distribution Function (EDF). JPM is an analytical approach while the EDF relies on empirical data to build

the joint probability mass function. Eq. (1) presents the joint probability density function f for JPM and Eq. (2) gives joint probability mass function for EDF model.

$$f(x_1, x_2, \dots, x_N) = \frac{1}{C} f_{X_1} \cdot f_{X_2} \cdots f_{X_N} \cdot g(x_1, x_2, \dots, x_N) \quad (1)$$

$$\text{with } C = \int_{\Omega} \cdots \int_{\Omega} f_{X_1} \cdot f_{X_2} \cdots f_{X_N} \cdot g(x_1, x_2, \dots, x_N) dx_1 dx_2 \cdots dx_N$$

f_{X_i} is marginal distribution function, and $g(x_1, x_2, \dots, x_N)$ is correlation function

$$f_{Z_1 Z_2 Z_3}(a, b, c) = \frac{1}{M} \sum_{i=1}^M I(z_{1i} = a, z_{2i} = b, z_{3i} = c) \quad (2)$$

where

$$I(z_{1i} = a, z_{2i} = b, z_{3i} = c) = \begin{cases} 1 & \text{if true} \\ 0 & \text{if false} \end{cases}$$

JPDM uses Probability of Success (POS) as the ultimate measure of optimality and this is given by Eq. (3) from [Ref. 1]. $Criteria_1$ and $Criteria_2$ are two system objectives that are investigated $Constrain_1$ and $Constrain_2$ are limitation for the two criteria and construct the area of interest

$$POS = P(Criteria_1 \in Constrain_1, Criteria_2 \in Constrain_2) \quad (3)$$

The two-dimensional representation of JPDM environment is shown in Figure 1. The fact that JPDM is a multi-criteria design technique with a probabilistic theme is clear in the figure. One of its strongest advantages is that it captures the uncertainties directly by applying the probability distributions to the input design parameters which result in the criteria being random variables. In Figure 1, the marginal distributions for the criteria are shown in blue along the axes. The POS, another advantage, is obtained by integrating the joint criterion distribution over the area of criterion values that are of interest to the customer. Finally, JPDM creates a compensatory technique for product selection (i.e. choosing the best amongst a finite set of alternatives) that allows comparison of alternatives on an equal basis.

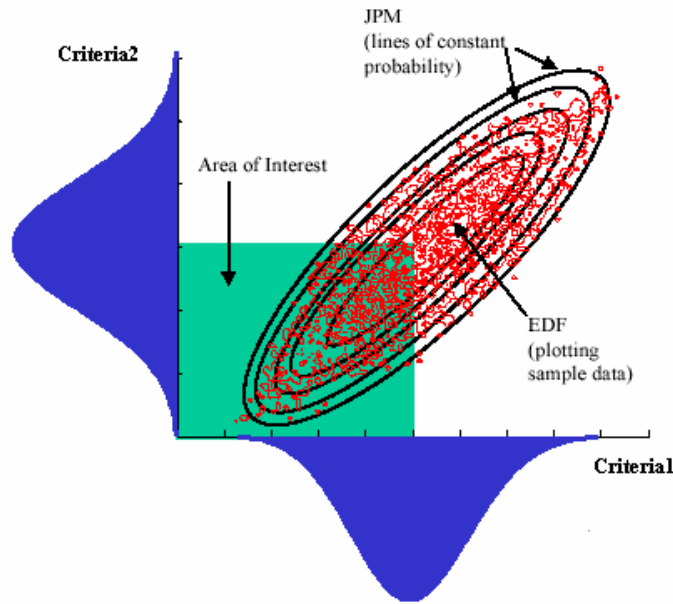


FIGURE 1: JPDM TECHNIQUE VISUALIZATION

JPDM also has some application limitations. When an analytical form of the criteria as a function of design variables is not available, empirical or simulation data must be used through the EDF approach. In the EDF model, accurate data is needed for the criteria. Such data is often not easy to get in conceptual and preliminary design phases. If an analytical expression is available and the JPM model is used, a correlation function is required, which also may not be available in early stages of design.

The Procedure for Running JPDM Using EDF Model

An example is presented to show how to use EDF model to conduct concept selection problem. The flow of data in this procedure is shown on Figure 2. This example is also relevant for this grant since it was connected to other work on-going in the NASA Systems Analysis Branch in the area of Personal Air Vehicles (PAV) under the RASC program. In this example, it is desired to select the most viable PAV concept from amongst three competing concepts: a version of the Robinson R-44 helicopter, a version of the Groen Brothers Aviation Hawk4 gyroplane, and the Bell/Augusta 609 tiltrotor. The actual code for executing this problem using JPDM is described in the Appendix to this report.

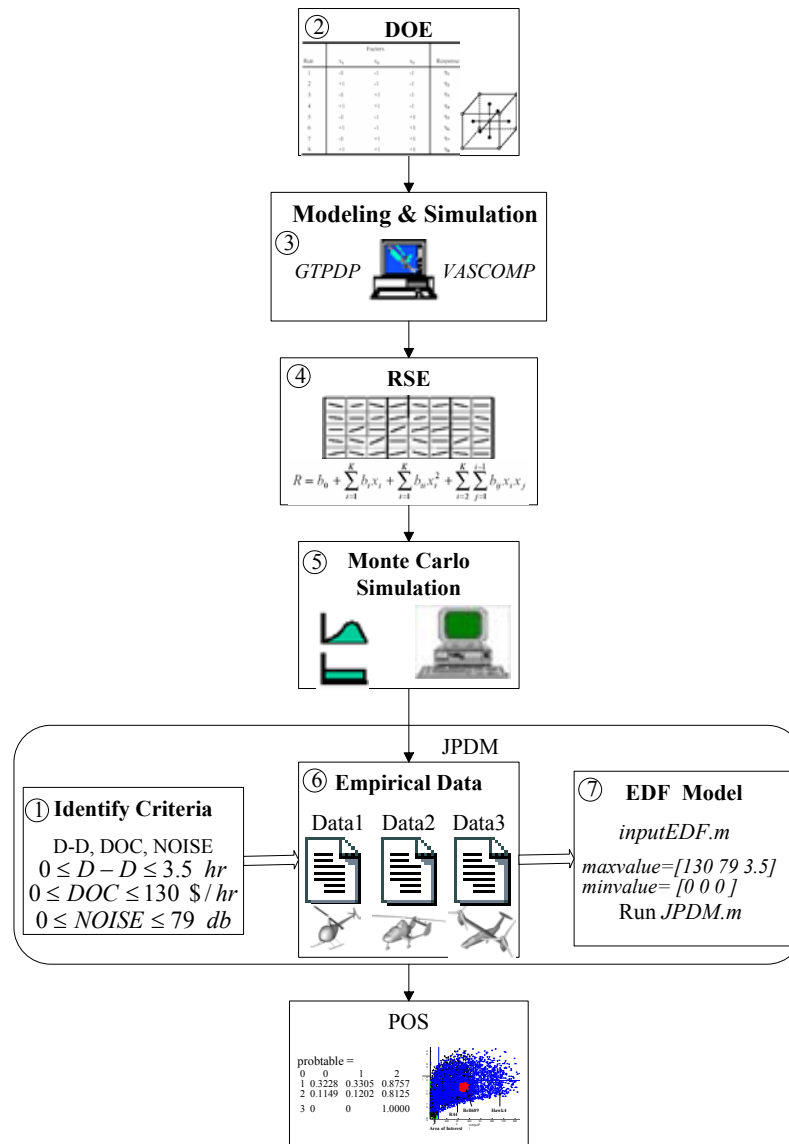


FIGURE 2: FLOW CHART OF PRODUCT SELECTION PROCEDURE USING EDF MODEL

Identify the Criteria and Their Range of Interest

Before running JPDM, the criteria which evaluate the customer requirements should be identified first. In the example of PAV concept selection problem, three criteria are identified. They are doorstep to destination (D-D) time, direct operating cost (DOC) and noise (NOISE). Viability of a design concept is measured by the probability of satisfying certain desired levels of the doorstep to destination time, direct operating cost and noise. All the criteria are desired to be as small as possible, so zero as a minimum value is assigned to all the criteria. Upper limits that cannot be violated are identified as 3.5 hrs, 130 \$/hr, 79 db for doorstep to destination time, DOC and noise respectively. These values create the constraints for the three criteria: $0 \leq D-D \leq 3.5$ hr, $0 \leq DOC \leq 130$ \$/hr and $0 \leq NOISE \leq 79$ db.

Obtain Empirical Data

Empirical data can be obtained from different sources. In this example, data were generated with the combination of aircraft design codes, Response Surface Equations (RSEs), and the Monte Carlo Simulation and then used for the EDF. An RSE is a second-order quadratic equation developed from the Response Surface Methodology (RSM) multivariate regression technique to model the responses of a complex system. Before RSEs are constructed, modeling and simulation is conducted using sizing and performance codes relevant to each vehicle such as GTPDP (helicopters, [Ref. 2]) and VASCOMP (tiltrotor, [Ref. 3]). The outcomes serve as the regression data guided intelligently through the Design of Experiment (DoE) technique. Once the response data is collected, RSEs can be generated using a statistical analysis package called JMP [Ref. 4]. When RSEs are developed, 10,000 samples are generated through the Monte Carlo Simulation (MCS) using Crystal Ball software. In the phase of MCS, uncertainty is propagated to the system level by defining appropriate probability distributions to uncertain mission requirements, vehicle attributes and infused technology. The sample data for each concept is saved as Data1 Data2 and Data 3. The data files have to contain the data in an $m-n$ matrix, m being the number of rows, i.e. samples, n being the number of columns, i.e. criterion. The number used after "Data" corresponds to the concept to be evaluated.

Run EDF Model

The JPDM was coded using MATLAB and FORTRAN. The flow of information within the program is outlined in the flow chart of Figure 3 [Ref. 1]. Each of these files is also contained on the CD supplied with this report. The values of some parameters should be modified before the program can work for the specific problem. In the inputsEDF.m file, the elements in the matrices called *maxvalue* and *minvalue* should be changed to the upper and lower limits of the criteria identified before. Thus, for this specific case, *maxvalue*=[130 79 3.5] and *minvalue*=[0 0 0]. It should be noted that the order of the criteria in the data file and the order of the criteria in the above two matrices should be identical. In other words, if the first column in the data files stands for criterion DOC, the first elements in the matrices *maxvalue* and *minvalue* have to be the upper and lower values of DOC. The numbers in the matrix *crplots* indicates which two criteria will be evaluated for calculating the Probability of Success and creating the graphs. For example, if *crplots*= [1 2] the POS and graphs will be generated for the criterion 1 and 2 (DOC vs. NOISE). In addition, *name(1)* and *name(2)* should be changed to the appropriate name of the criteria that will be displayed in the graphs.

After the above modifications are finished, the *JPDM.m* MATLAB file is run. The program will calculate the POS and create the graphs using EDF model. In this example, MATLAB gives the solution denoted in Table 1. The joint POS and univariate probabilities of for DOC, D-D and NOISE are shown for the three concepts. From a product selection point of view, the R-44 version has the greatest chance of success considering all three criteria simultaneously. Graphical representation of NOISE-DOC slice is shown in Figure 4. Similarly, the other two two-dimensional graphs (DOC vs. D-D and NOISE vs. D-D) can be obtained by changing the parameters in the matrix *crplots*.

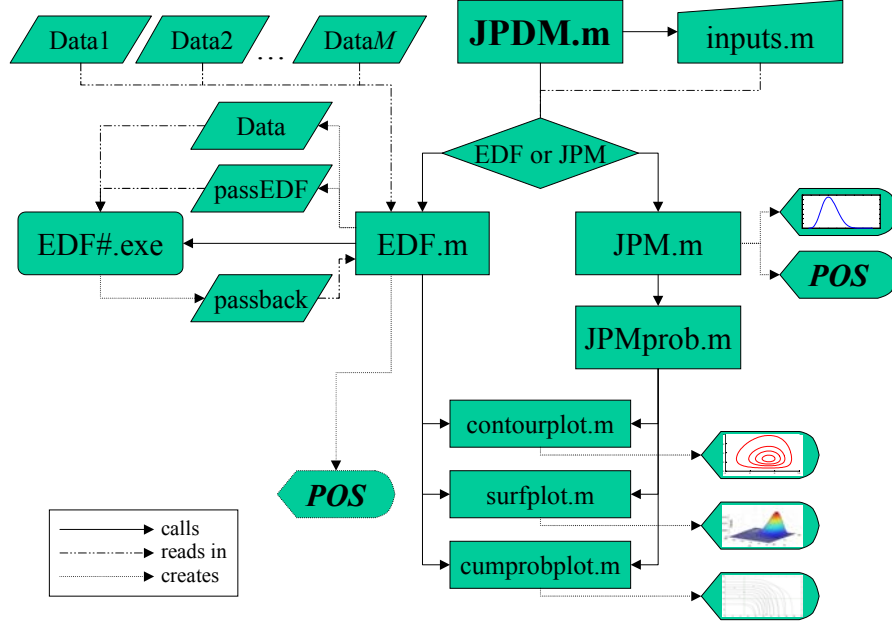


FIGURE 3: FLOWCHART OF THE JOINT PROBABILISTIC DECISION MAKING TECHNIQUE

TABLE I: EXAMPLE JPDM RESULTS- POS AND UNIVARIATE DISTRIBUTIONS

	Joint Probability of Success	Univariate Probability for Criteria DOC	Univariate Probability for Criteria NOISE	Univariate Probability for Criteria D-D
R-44	0.1448	0.3305	0.8757	0.4378
HAWK 4	0.0689	0.1202	0.8125	0.3716
B/A-609	0	0	1.0000	0.9992

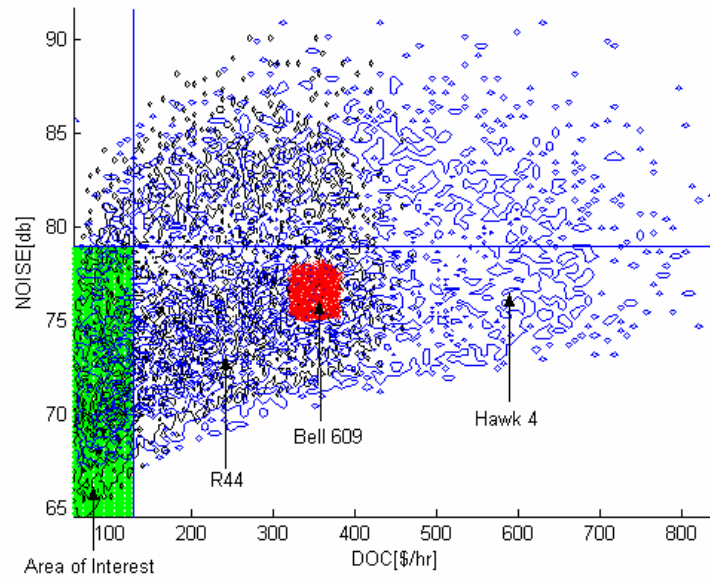


FIGURE 4: JOINT PROBABILITY DISTRIBUTION

2. Physical Programming (PP)

Physical Programming (PP) is multi-criteria optimization method that requests physically motivated information from the designer and produces a problem statement that reflects the realistic texture of the designer's preferences. It is described extensively in Refs. [5, 6, 7]. It seeks to avoid the traditional problem in the multiple criteria domain: the need to choose weightings for the criteria. In PP, after identifying the design parameters and design metrics, the designer specifies the class-type (Figure 5) for each metric and then also defines the ranges of different degrees of desirability for each design metric in the corresponding class function (Figure 6). Class types can be either soft or hard, depending on whether there is a crisp delineation between acceptable and unacceptable levels (hard) or a continuum of acceptability (soft). For example, Class 1-S indicates a metric for which smaller is better. Further, through the process in Figure 6, the degree to which levels of the metric are desirable can be defined. All soft class-function will become constituent components of the aggregate objective function (defined below in Eqs. (4)-(13)) that is minimized. The mapping which defines the path from this design parameters to aggregate objective function are shown in Figure 7.

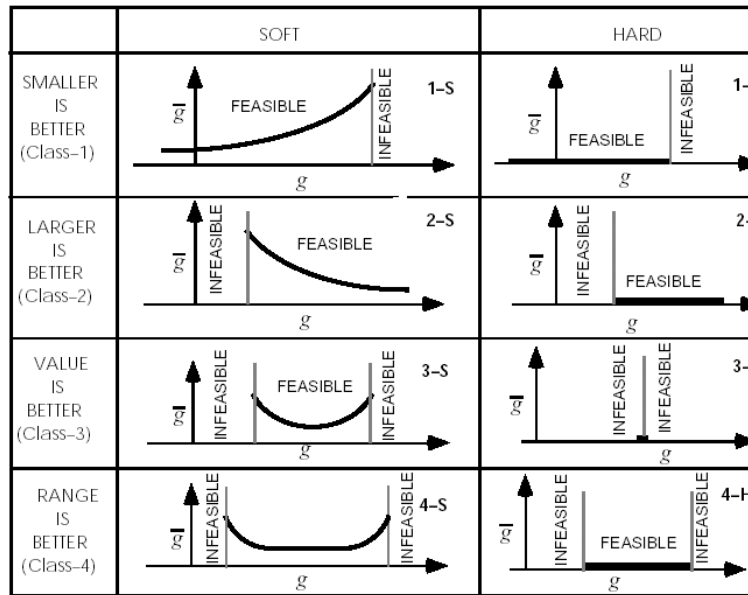


FIGURE 5: CLASSIFICATION OF DESIGN METRICS

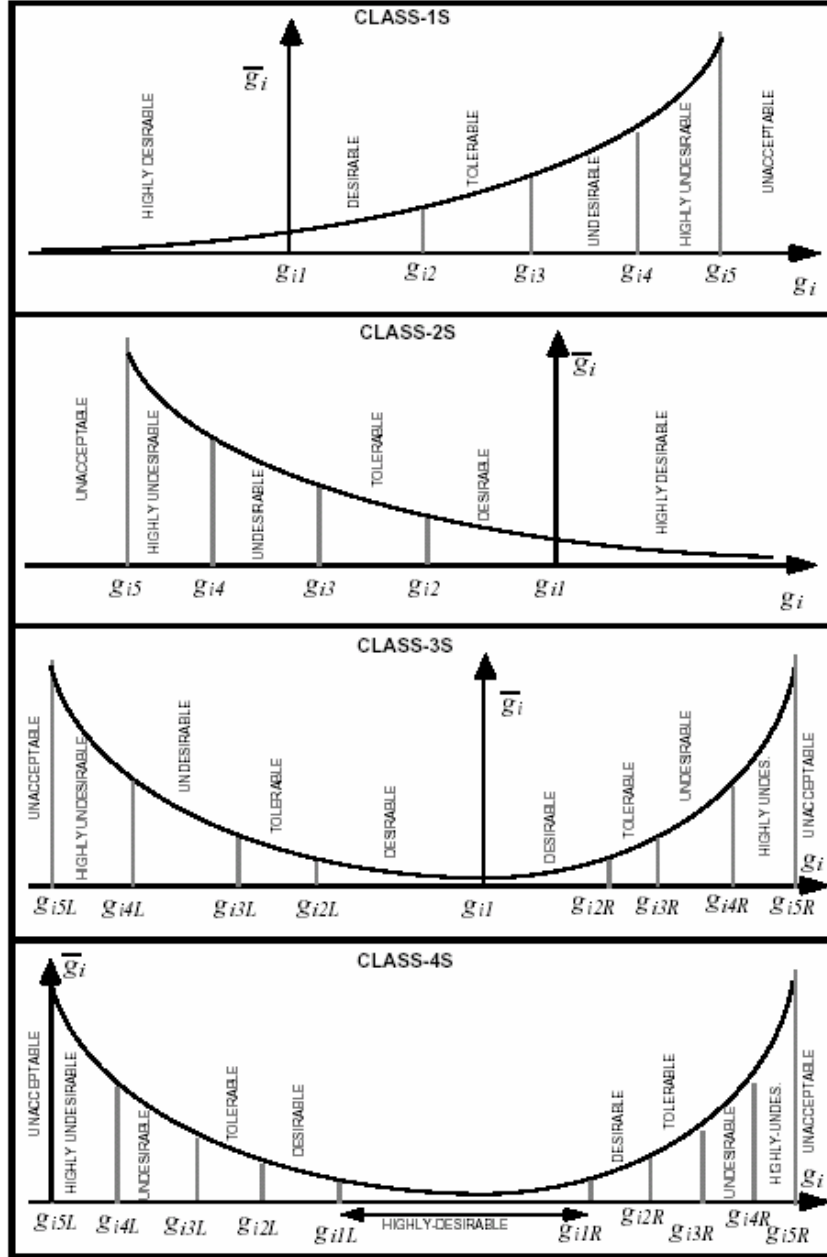


FIGURE 6: CLASS-FUNCTION RANGES FOR THE I-TH GENERIC METRIC

$$\text{Minimize: } Z(x) = \log_{10} \left[\frac{1}{n_{sc}} \sum_{i=1}^{n_{sc}} \overline{g_i} [g_i(x)] \right] \quad (4)$$

Subject to:

$$g_i(x) \leq g_{i5} \quad (\text{for class 1-S}) \quad (5)$$

$$g_i(x) \geq g_{i5} \quad (\text{for class 2-S}) \quad (6)$$

$$g_{i5L} \leq g_i(x) \leq g_{i5R} \quad (\text{for class 3-S}) \quad (7)$$

$$g_{iSL} \leq g_i(x) \leq g_{iSR} \quad (\text{for class 4-S}) \quad (8)$$

$$g_i(x) \leq g_{iM} \quad (\text{for class 1-H}) \quad (9)$$

$$g_i(x) \geq g_{iM} \quad (\text{for class 2-H}) \quad (10)$$

$$g_{iM} = g_{i.val} \quad (\text{for class 3-H}) \quad (11)$$

$$g_{iM} \leq g_i(x) \leq g_{iM} \quad (\text{for class 4-H}) \quad (12)$$

$$x_{jm} \leq x_j \leq x_{jM} \quad (\text{for des. var. constraints}) \quad (13)$$

where $n_{sc} = \#$ of soft classes.

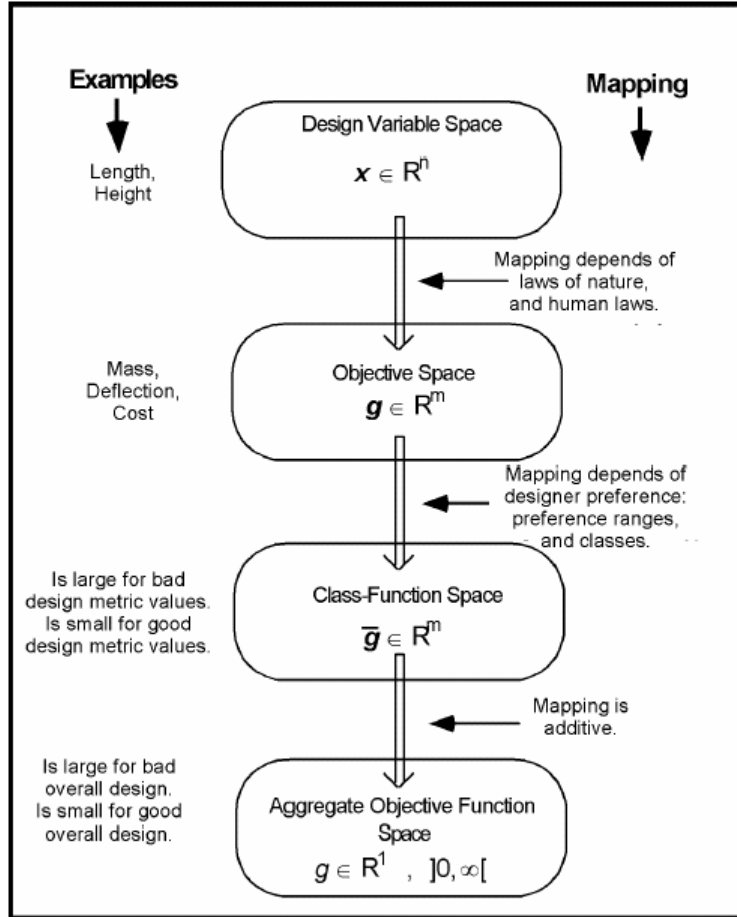


FIGURE 7: PHYSICAL PROGRAMMING MAPPINGS

PP, as one of the multiobjective design methods, has some advantages over the conditional design methods. First, the formation of an aggregate objective function usually involves a largely ill-defined trial-and-error weight-tweaking process that may be a source of frustration and significant inefficiency. PP captures the designer's physical understanding of the desired design outcome in forming the aggregate objective function, eliminating the uncertain and time-consuming process of scalar criteria weighting. Secondly, PP attempts to offer a problem formulation and solution framework that conforms to real-life design. The notion that attempts to use numerical weights to describe designer preference is considered as ineffective. PP does not require the designer to specify optimization weights in the problem formulation phase, and it allows designer to define their preference in physically meaningful terms. This removes the frustrating process of weight tweaking entirely.

PP also has its own drawback. Firstly, PP requires a priori selection of range parameters for each of the objective functions. Such information may not be known at the outset (e.g. “Is gross weight likely to range between 100,000-200,000 lbs in my design space or 200,000-300,000lbs?”). In problem formulation phase, the designer’s time is mostly consumed in exploring the implication of the various physical meaningful preference choices. Secondly, PP only provides information for one design scenario at a time. To capture a variety of design scenarios, which represent different preferences on the design metrics, a set of preference structures should be built and tested. **Thirdly, PP is deterministic design method and does not capture the uncertainties due to incomplete information existing in design space and environment.** This latter issue is very significant.

3. Dempster-Shafer (D-S) Theory

Dempster-Shafer (D-S) theory of evidence (Ref. [8]) is a framework for integrating pieces of information from independent sources, in order to improve the decision making process. Unlike JPDM, D-S theory does not employ a probabilistic mentality. Instead, the concept of belief is used. Therefore, the D-S theory may be applied to integrate judgmental adjustments from several experts as required by the case at hand. The judgements for several candidate adjustments form basic belief assignments (BBA) over the set a Universe of Discourse U , also called Frame of Discernment, which is a set of mutually exclusive alternatives, in a way that the mass of belief assigned to the set varies from 0 (complete ignorance) to 1 (perfect knowledge). The frame of discernment may consist of the possible values of an attribute.

The basic belief assignment (BBA) is a mapping m from the set of all subsets A of U to $[0, 1]$, such that

$$m(\phi) = 0 \quad (14)$$

$$\sum_{A \subseteq \Omega} m(A) = 1 \quad (15)$$

Associated with m , the *belief* or *credibility*, and *plausibility* measures are defined by

$$\text{bel}(A) = \sum_{B \subseteq A} m(B) \quad (16)$$

$$\text{pl}(A) = \sum_{A \cap B \neq \phi} m(B) \quad (17)$$

$\text{bel}(S)$ summarizes all our reasons to believe A while $\text{pl}(A)$ expresses how much we should believe in A if all currently unknown facts were to support A . Thus the $\text{bel}(A)$ is not greater than $\text{pl}(A)$ and true belief in A will be somewhere in the interval $[\text{bel}(A), \text{pl}(A)]$.

Given two BBAs, m_1 and m_2 , the combined belief is computed using an important operation in the D-S theory. This operation is referred as “Dempster’s rule of combination”, which yields a new BBA $m = m_1 + m_2$ defined as:

$$m(A) = \frac{\sum_{B \cap C = A} m_1(B)m_2(C)}{\sum_{B \cap C \neq \phi} m_1(B)m_2(C)}, A \neq \phi \quad (18)$$

The Dempster-Shafer theory can be used to represent situations in which different kinds of ignorance exist in our knowledge about a phenomenon or a system. Thus it is not tied to the need for input probability distributions (as JPDM is). The belief functions are based on a basic probability assignment, which is a measure of the belief committed exactly to a given hypothesis or a subset of the frame of discernment. The theory has been applied to several decision making problems such as the selection of bearings for a specific application and for multiple objective optimization of engineering systems. Since most practical design problems are solved iteratively, the computational information accumulated in each

iteration can be used to develop an evidence-based model using Dempster-Shafer theory for solving design problems more efficiently.

This theory also has its own limitations. If the source of evidence is not independent, it can lead to misleading and counter-intuitive results. Secondly, in classical decision analysis, it remains necessary to enumerate the potential states of nature and to assign utilities. This task can be overwhelming when complex scenarios are considered.

4. Summary Assessments

From the analysis above, JPDM, PP and D-S theory are all multi-criteria design approaches. Only JPDM and D-S theory address uncertainty in the design problem in a direct way. PP allows the designer to express design preference in a flexible and physical meaningful manner, thus dealing with uncertainty in the formation of the objective function itself. In this way, PP eliminates the frustrating process of weight tweaking which the weight-based approaches have. This indicates PP is easier to use when weighting of criteria is difficult, risky, or not possible.

JPDM has the ability to capture and analyze uncertainties, so it is good for the design problem with incomplete information. This is quite important in conceptual and preliminary aerospace vehicle design phases, when key information is known only to a partial extent. Further, in practice, more uncertainties exist in the operational environment of a vehicle as well as in computer model fidelity and technology insertion. Thus, JPDM is better than PP or D-S for practical design problem under explicit uncertain information.

D-S theory is a generalization of probability theory with special advantages in its treatment of ambiguous data and the ignorance arising from it. This theory also has the ability to capture the uncertainties by using the belief functions that are based on a basic probability assignment. However, it computes the probability that evidence supports the proposition using belief intervals rather than computing the probability of a proposition. It can provide help for decision making when the probabilistic information is incomplete.

According to the analysis above, the three techniques and the associated problem characteristics for which they are well suitable to solve are shown in Figure 8.

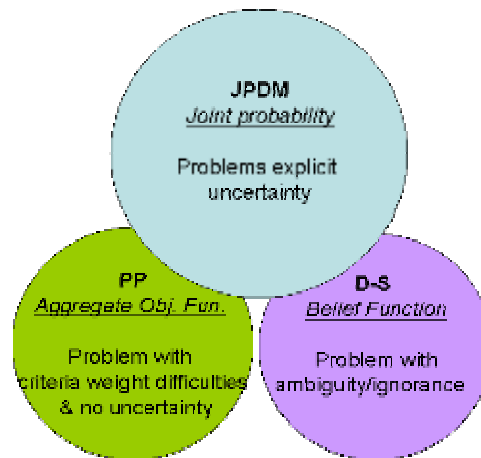


FIGURE 8: COMPARISON OF THREE MULTI-CRITERIA DECISION-MAKING TECHNIQUES

Task B: Development and Implementation of Technology Selection Methods

The focus of Task B efforts for Year 3 was three fold, including:

- Construct and document software implementation for the TIES method based on results of first and second year of research
- Continue exploration of new methods, guided by Year 1 and 2 results in conjunction with SAB initiatives
- Publish results of research in relevant conferences and journals

The underlying theme of Year 3 efforts was to create an initial capability for the Systems Analysis Branch at NASA Langley to implement the TIES method. In effect, mature the method to the point that a technology transfer could occur so as to facilitate robust annual technology benefit assessments for the sponsor. To accomplish this end, ASDL implemented the TIES method into the Advanced Design Methods (class number AE8804) within the graduate program in the School of Aerospace Engineering at Georgia Tech. To test the robustness and ease of implementation, ASDL believed that if a group of first year graduate students with no knowledge of the techniques or analysis tools utilized in the TIES method could in fact learn and apply the method within a semester course, the method would be mature enough to transfer as a package to the sponsor. Given this goal, ASDL implemented the TIES method as a class project for the past 3 years with a culmination of all the method advancements included in the Fall 2002 class.

Within the graduate course, the 51 first year graduate students were divided into 17 teams of 3 people. Each team was provided with a baseline aircraft model, the TIES tutorial, and a project description outlining the requirements for the project. The baseline aircraft models were obtained from the sponsor in the Summer of 2001 and corresponded to the fleet of aircraft being utilized for Enterprise technology benefit assessments. Additionally, the technologies utilized in the project were also provided (and consistent) with the sponsor assessments from 2001. Each team implemented the TIES process and was required to give a final presentation and report at the end of the semester. The team with the superior report is provided as an appendix, along with the tutorial, with the project description provided herein.

Although the students were not experts in the techniques and software utilized in the TIES method, the final product delivered by the students indicates that the maturity of the TIES method is ready for transfer to the sponsor. The students implemented each step with minimal guidance and supervision. Given this result, a tutorial with sample files is also contained on the CD so as to facilitate the use of the TIES method within the Systems Analysis Branch. With this tutorial, the objectives of Year 3 were achieved.

AE 8804A: Advanced Design Methods I

Fall 2002 Design Project Description

Prof. Dimitri Mavris

Asst Instructor: Dr. Michelle R. Kirby

Important dates

Deliverable 1	Detailed GANTT Chart of the Project:	September 27 th
Deliverable 2	Steps 1 – 3 Report Due:	October 7 th
Deliverable 3	Steps 4 – 5 Report Due:	October 23 rd
Deliverable 4	Steps 6 – 7 Report Due:	November 13 th
Deliverable 5	Step 8 Report Due:	December 6 th

(Compiled in the Final Deliverable)

Final Deliverable Report Due: Friday, December 6th by noon to Dr. Kirby in both paper and electronic format (MS Word only). Each of the deliverables should be building toward this final report.

Presentations: 40 minute presentation limit

Teams will present their projects the week of December 2nd. Details of the dates and time will be announced at a later date.

With each report, the following is required and must be signed and dated by each team member:

1. A formal declaration that the work and ideas contained within the report are solely those of the team member except where explicitly referenced or cited from another source.
2. A list of which team member performed a given requirement and who wrote a given section of the report.
3. A table consisting of an evaluation of each team member to the team goals as evaluated by others. A sample will be provided as the first deliverable approaches.

Important Information

Website for tutorials, spreadsheets, project files, and sample scripts:

<http://www.asdl.gatech.edu/people/mkirby/Class/index.html>

A report format guideline will be posted on the class website shortly as well as a link to guidelines for writing a research paper and how to cite reference material.

Objective

The primary objective of the project is for you to learn the advanced design techniques taught in class. The focus of the project will be an exercise of the Technology Identification, Evaluation, and Selection (TIES) method. This mature method entails an eight-step process that you will implement for different aerospace vehicles. At the end of project, you should have learned the following:

1. How to run synthesis/sizing and economical analysis tools
2. Design of Experiments and the usefulness of the method
3. How to use the statistical package, JMP
4. How to generate Response Surface Equations and check the goodness
5. How to model uncertainty through Monte Carlo simulations
6. Sensitivities of performance and economic metrics to design variables

7. Sensitivities of economic metrics to economic uncertainty
8. How to simulate technology impacts on a vehicle
9. How to choose the proper mix of technologies to meet customer requirements
10. How to use and create UNIX shell scripts
11. How to write a research paper

Each team is given a baseline vehicle which is modeled in the Flight Optimization System (FLOPS) code and the Aircraft Life Cycle Cost Analysis (ALCCA) accessible from class website. Each vehicle is representative of a current commercial vehicle or a notional future concept. You will be implementing all of the steps of the TIES method for the projects, in addition to expansions of the current method. Some information of particular steps will be provided to reduce the workload, specifically, the metrics, design variables of interest, scripts, and MS Excel® templates. All other steps will be implemented by your team. References associated with the TIES method are listed below and can be obtained from the class website or from: <http://www.asdl.gatech.edu/publications>.

1. Kirby, M.R., Mavris, D.N., "A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment," SAE-2001-01-3018.
2. Kirby, M.R., Mavris, D.N., "A Method for Technology Selection Based on Benefit, Available Schedule and Budget Resources," SAE Paper No. 2000-01-5563.
3. Kirby, M. R. and D. N. Mavris, "Forecasting Technology Uncertainty in Preliminary Aircraft Design," SAE paper no. 1999-01-5631.
4. Mavris, D.N., Kirby, M.R., "Technology Identification, Evaluation, and Selection for Commercial Transport Aircraft", 58th Annual Conference Of Society of Allied Weight Engineers, San Jose, California 24-26 May, 1999.
5. Mavris, D.N., Kirby, M.R., Qiu, S., "Technology Impact Forecasting for a High Speed Civil Transport", SAE-985547.
6. Mavris, D.N., Mantis, G., Kirby, M.R. "Demonstration of a Probabilistic Technique for the Determination of Economic Viability," SAE-975585.
7. Kirby, M.R., Mavris, D.N., "An Approach for the Intelligent Assessment of Future Technology Portfolios," AIAA 2002-0515.

The 8 steps contained in the TIES method are

1. Problem definition
2. Baseline and alternative concepts identification
3. Modeling and simulation
4. Design space exploration
5. Determination of system feasibility/viability: probability of success
6. Specify Technology Alternatives
7. Assess Technology Alternatives
8. Select Best Family of Alternatives

The requirements you will need to fulfill for the current project are listed as part of each step described below. Your effort in this project should not be limited to the pre-specified requirements. Original thought and creativity are desired and recommended.

Step 1: problem definition

The primary objective of Step 1 is to map the “voice of the customer” to the “voice of the engineer” as a response to some societal need as determined through a Quality Function Deployment as learned in the Systems Design for Affordability class. The result of this step is the identification of the system level metrics which capture the customer requirements. The metrics of interest are provided for you in Table II. As you can see, the target and/or constraint values are not provided and are to be determined (TBD) by your team. Suggestions for values include: NASA (<http://www.hq.nasa.gov/office/aero/>), Boeing and Airbus web sites for competitive economic values, Air Transportation Association web site (<http://www.airlines.org/public/industry/>), potential city pairs for runway lengths, FAA web site for operational restrictions, and so on. Also, the * metrics should have 2 targets. One for the year 2007 (10 year goal) for a 25% reduction from your baseline levels, and the other for the year 2022 (25 year goal) for a 50% reduction from your baseline values.

Note, the following metrics are NOT calculated within FLOPS/ALCCA and must be calculated off-line and with the results from your analysis:

$$CO_2/ASM = 3.155 \frac{\text{Mission_Block_Fuel}}{(\text{Total_Pax_Capacity}) * (\text{Range})}, \text{ and } WAWt = \frac{\text{Wing_wt}}{\text{Wing_Area}}$$

Requirements for Step 1:

1. Define the need for your aircraft, for example, projected passenger traffic and cargo growth, congested airways, or changing regulations.
2. Define potential markets in which the aircraft will be utilized
3. Define competitors
4. Define the metrics in Table II
5. Describe why the metrics are important to your vehicle, what is the qualitative significance of lowering or increasing the metric values, i.e., what options or benefits does it provide to your vehicle.
6. Who is the metric responding to, e.g., Acq \$ is a metric of concern to the airlines. The more they pay for an aircraft, the larger the passenger ticket price needed to pay for the aircraft for the airline to make a particular profit, the more the investment the airlines must make, etc.
7. Identify target or constraint values for each, suggestions for this are market studies by Boeing and Airbus, FAA regulations, airport compatibility, etc. You can also look at the baseline output file for starting values to get an estimate. An example for a target would be a TOFL of less than 11,000 ft for a HSCT. This is because most major airport runway lengths are less than 11,000 ft and the airplane must be able to take off without modifications to ANY existing airports. For a smaller capacity aircraft, being able to land or takeoff from more airports is important and a smaller runway length constraint would be important. Hint: you have a 50 pax vehicle, optimizing utilization in different airports would be beneficial, think of PDK to Lake Charles, LA and find the associated runway lengths.

TABLE II: SYSTEM LEVEL METRICS

Parameter	Target/ Constraint
Performance	
Approach Speed (Vapp)	TBD
Landing Field Length (LdgFL)	TBD
Takeoff Field Length (TOFL)	TBD
CO ₂ /ASM (CO ₂)*	TBD
NO _x /ASM (NO _x)*	TBD
Takeoff Gross Weight (TOGW)	TBD
Economics	
Acquisition Price (Acq \$)	TBD
Research, Development, Testing, and Evaluation Costs (RDT&E)	TBD
Average Required Yield per Revenue Passenger Mile (\$/RPM)	TBD
Total Airplane Related Operating Costs (TAROC)	TBD
Direct Operating Cost plus Interest (DOC+I)*	TBD
Misc	
Wing Aerial wt (WAWt)	TBD

Step 2: Baseline and alternative concepts identification

Once the customer requirements are defined in terms of *quantifiable* engineering parameters, the thrust of the TIES method begins with the definition of the concept space. Initially, the experience, knowledge, and intuition of the designer is utilized to identify a potential class of vehicles and provides the methodology with a starting point for selecting potential solutions to satisfy the customer requirements. The focus of this

step is two-fold: identify the space of alternative concepts that is based on a defined class of vehicles, and establish the geometric and propulsive design space for which system feasibility is initially sought.

Space of alternatives

In the design of any complex system, there exists a plethora of combinations of particular subsystems or system characteristics that may satisfy the problem at hand. For example, how many engines are needed? What type of high lift system is needed? Is a horizontal stabilizer preferred over a canard? A functional and structured means of decomposing the system and identifying component options is through the use of a Morphological analysis. The Morphological Matrix is an ordered Morphological analysis that is formed by identifying the major functions or characteristics of a system on the vertical scale and all the possible alternatives (or system attributes) for satisfying the characteristics on the horizontal scale. In essence, this is where mature and immature technology alternatives are defined. Once the matrix is populated, an alternative design concept is defined as a mix of the characteristic alternatives. All possible design alternative combinations define the *alternative concept space*. In general, one alternative concept is established to begin the feasibility investigation and will be called the *baseline concept* and is typically drawn from mature or present day technologies.

Design Space

Once the baseline concept is defined from the alternative concept space, the baseline may be further decomposed into product and process characteristics. This can be performed via a Morphological Matrix or through brainstorming sessions. The metrics for your baseline are broken down into product characteristics (or design variables) in Table III. These “control” variables define the design space you will investigate for technical feasibility once you have identified *appropriate* ranges for each variable. The control variables are listed as the way they appear in FLOPS, the associated namelist, and a description of the variable.

NOTE: the baseline files that you have in your accounts corresponds to a vehicle that could be built in 1997 with the technologies available at that time. These vehicles are representative of the systems that NASA is considering in the Aerospace Technology Enterprise focus of the future. Please refer to NASA’s web site at <http://www.hq.nasa.gov/office/aero> for more information. The technology sets and some objectives were founded based on the NASA efforts and the 10 and 25 years goals that were set forth by the NASA Administrator to guide and focus research endeavors of the future. This implies that your project is relevant to the research currently being conducted in the aerospace industry.

TABLE III: DESIGN VARIABLE DESCRIPTION

Variable	Namelist	Description
SW	CONFIN	Wing area
TWR	CONFIN	Thrust to weight ratio
AR	CONFIN	Wing aspect ratio
TR	CONFIN	Wing taper ratio
TOC (1)	WTIN	Wing thickness-to-chord ratio at root
TOC (3)	WTIN	Wing thickness-to-chord ratio at tip
SWEEP	WTIN	Wing quarter-chord sweep
ARHT	WTIN	HT aspect ratio
TRHT	WTIN	HT taper ratio
TCHT	WTIN	HT thickness-to-chord ratio
SHT	WTIN	HT area
ARVT	WTIN	VT aspect ratio
TRVT	WTIN	VT taper ratio
TCVT	WTIN	VT thickness-to-chord ratio
SVT	WTIN	VT area

Requirements for Step 2:

1. Describe your baseline and identify what class of vehicle it is, i.e., long range, widebody, etc and provide a notational 3 view. Create a Morphological Matrix of your vehicle based on the class of vehicle that it falls into. You will need two major components of your matrix including mission requirements and vehicle characteristics. Once you create the Matrix, please identify the baseline as a picture with the baseline characteristics circle. Be as exhaustive as possible and note that there is no single or right Morphological Matrix. This is a tools for brainstorming.
2. Define “workable” ranges for the design variables in Table III, where workable implies that FLOPS can achieve a converged solution for any combination of variables. Note, this is probably the most time consuming and difficult aspect of the project. You will need patience. ☺ Suggestions would be a deviation of +/- 20-30% from your baseline values if you cannot find any information. Note, FLOPS is HIGHLY sensitive to variations in T/W and W/S ratios, especially T/W. You may not want to deviate as much as 20-30 %. Also, consider which of the design variables provided will have the most significant impact on the system and use those as drivers to determine your ranges.

Step 3: Modeling and simulation

The modeling and simulation environment is provided to you as the FLOPS and ALCCA executable. All teams are provided a FLOPS Version 5.95 and an ALCCA Version 5 manual. I would strongly suggest understanding ALL the inputs that describe your vehicle and the inputs that are omitted (set at default values). You should play with the program a bit to get a feel for how it works. ⇔ Note, you should make a backup of all the files that are provided to you before you make ANY modifications to the baseline files. ⇐

Requirements for Step 3:

1. Describe the mission that is used to size your vehicle.
2. What are the different segments of the mission trying to optimize and/or how is the aircraft operating for a given segment. For example, you could climb for minimum fuel burn or minimum time. Specify each segment or what power setting are you using for approach.
3. What are the assumptions associated with sizing and evaluating your vehicle, both from a sizing perspective and an economic perspective?
4. Provide a figure representing your mission profile
5. Plot your engine performance deck in the following formats
 1. Thrust v. Mach for different altitudes
 2. Fuel flow v. Mach for different altitudes

Do both of these at max power

6. Plot your baseline drag polars for different Mach numbers at sea level and at your cruise altitude. (You can find this information in your baseline output file.)
7. From your baseline file, establish the following:
 - A) Airframe manufacturer related information
 - What is the manufacturer’s cash flow for your vehicle?
 - What are the elements composing the cash flow?
 - What is the breakeven unit number and when in the program does it occur?
 - Show the sensitivity of the manufacturer’s ROI as a function of Aircraft Price for different production quantities.
 - What is the production schedule? That is, how many aircraft are being produced per month and for how many years?
 - What is the acquisition cost of the aircraft as a function of units (in \log_{10} scale) produced? This should be a straight line.
 - Vary the production schedule (ie, number of years and how many per month) and show and discuss the impact on the manufacturer’s cash flow, the breakeven unit and time, and the acquisition price as a function of units produced.
 - B) Airline related information

- Provide a cost breakdown of the economics of your aircraft for the design and economic range. For example, a pie chart of the contributing elements of the TOC, DOC, and IOC.
- Show the sensitivity of the Airlines ROI as a function of Aircraft Price for different average yields.
- Show the ROI for the operation of your vehicle throughout its life, that is, how do the following vary with years of operation: operating cost, interest, depreciation, earnings before tax, net earnings, net cash flow, and discounted cash flow. Define each of these terms.

Step 4: Design space exploration

Before you begin the design space exploration, establish datum values for all the metrics listed in Table II. You can do this simply by looking at your baseline output file provided to you in your team account. You will be using the metamodel and Monte Carlo simulation method for the design space exploration.

Requirements for Step 4:

1. Describe what a Design of Experiments is. Why are you using Design of Experiments
2. What is an R^2 , a whole model test, a residual
3. Describe how to generate a Response Surface Equation (RSE)
4. Create RSEs of the metrics and describe which DoE you used
5. Create prediction profiles of the metrics to show the sensitivity of the response to the design parameters. Discuss the results and trends. Do they make sense
6. Describe the different means to evaluate the accuracy and goodness of your RSEs. Select a couple of approaches and show how accurate the RSEs are by providing the confidence intervals and error distributions and a description of how you came up with them. Run a confirmation test
7. You must run as many randomly generated cases as you had for your original DoE. Dr. Kirby has files that will set these up for you. Just email or go see her. Once you run these cases, import them into an MS Excel® file. Then take the **original** JMP file with the data from the original DoE you used and do a least squares analysis on each response. When the window pops up, each response will have a little red triangle beside it. Under the triangle go to “Save Columns” and select “Predicted Formula”. You must save the formula NOT the values. JMP will create new columns in your table. **IMPORTANT:** Save this as a new file. Then import your random design into the design variable settings columns (ie the -1 and 1). JMP will automatically update the equations. These now are your predicted values for the random cases. You can then import your actual data from the random cases that you obtained from FLOPS/ALCCA and get the % relative error to these random cases where the relative error is: $[(\text{predicted}-\text{actual})/\text{actual}]*100$. You will observe that the error for these cases is MUCH bigger than for the original DoE and the R^2 values. This step gives you a feel for how good a representation your RSE's are of your code at random points within your design space and plot with the distribution feature of JMP. Provide these distributions in your report
8. Provide the general form of the RSE and also the specific coefficients that you have (in an appendix in tabular form, where the appendix should be entitled “Design Space RSE Coefficients”). What is the general assumption of 2nd order RSE? How does that relate to the distributions you created in the previous requirement? Based on your answer, was a 2nd order RSE appropriate?
9. Create 2 contour plots (also called carpet plots or design plots) of TWR versus SW for your metrics and identify which metrics are constraining the design space based on the target and constraint values you identified in Step 1 for both the 10 and 25 year goals.
10. If you do not have a feasible space for either year, how much would you have to relax the active constraint to obtain a feasible space? What would be the consequences of doing so in terms of competitiveness or regulatory compliance?
11. Run a Monte Carlo Simulation on each RSE assuming a uniform distribution of all the design parameters. You have been provided with an MS Excel® spreadsheet which has a template

for the Crystal Ball macro of MS Excel®. Use 10,000 cases to generate the metric CDFs. Extract the results for the percentiles in 5% increments and use in MS Excel® to plot the results. What does the CDF represent?

12. From the 6th requirement in this list, determine an appropriate distribution for your error and then add that distribution to the original RSEs and rerun your Monte Carlo Simulation. Extract the data and compare the new CDFs to the CDFs that had no error term. What is the significance of the results

Step 5: Determine System Feasibility and viability

Once you have all your response CDFs, you need to determine how feasible and viable your design space is. If you have an unacceptable probability of success, you will need to infuse technology concepts in Step 6. Additionally, once you determine how feasible your design space is, you will then investigate the economic viability. If you are not feasible or viable, this step will serve as a benchmark of how much improvement is needed. For the economic viability, use the economic variables below and the optimized configuration that you will determine in the second requirement of this step.

TABLE IV ECONOMIC VARIABLES FOR THE PROJECT

Name	ALCCA Variable Name	ALCCA Namelist	Variable Number
Utilization	U	COPER	1
Production Quantity	NV	CMAN	2
Coach Load Factor	CLF	COPER	3
First Class Load Factor	FLF	COPER	4
Airline Return on Investment	RTRTNA	CMAN	5
Manufacturer Return on Investment	RTRTN	CMAN	6
Fuel Cost	COFL	COPER	7
Manufacturer's Learning Curve	LEARN1	CMAN	8
	LEARN2		9
	LEARN1A1		10
	LEARN1A2		11
	LEARN1A3		12
	LEARN1A4		13
	LEARN1FE1		14
	LEARN1FE2		15
Economic Range	SL (second array element)	COPER	16

Requirements for Step 5:

Feasibility

1. Take the CDF's you generated in the previous step and add an additional vertical line for your target or constraint value for the metrics. Where that line intersects your CDF is the probability of achieving your goal. If every bit of the CDF lies to the left of your target, 100% of your designs can achieve your target. You are feasible. CONGRATS! Which CDF do you use? The one with the error term or without and why? Provide a table that lists the percent feasible space for each metric.
2. Optimize your design variables with the desirability function in JMP, modify your FLOPS file (not the original, but a copy), and re-evaluate all of your metrics by running FLOPS with this new file. This will become your optimized configuration upon which you will apply the technology factors. Show a comparison of the new geometry to the original that was provided. Specifically, two tables, one for the change of the geometry settings and another for the resulting change in the metrics. Include three data columns for this latter table including the baseline metric value, the optimized baseline metric values, and the relative percent change of the optimized baseline values to the original baseline. This configuration will be used for the viability assessments below.
3. Identify some additional options that might make you vehicle feasible rather than just adding technologies.

Viability

4. Define ranges for the economic variables and define the variables themselves
5. Develop response surface equations (RSEs) for each economic metric from Table I as a function of the variables in Table IV for the optimized baseline you determined above.
6. Create prediction profiles for these as a function of your variables.
7. What is the R^2 for these RSE'S?
8. Is there a residual? What does a residual mean?
9. Define shape functions for each of the economic variables chosen within the Crystal Ball program. Run a Monte Carlo Simulation on your RSEs and extract the cumulative Distribution Functions (CDFs) and Probability Density Functions (PDFs) for each metric.
10. Identify the probability of meeting your economic metric targets by adding in target or constraints values to the CDF's
11. What is implied by economic uncertainty?
12. Assume the following operational scenarios to modify your shape functions:
 - 1) Isolation: the U.S. is isolated to the world, no international travel is allowed, thus the economic mission, utilization, and load factor will be affected for the larger vehicles.
 - 2) No international oil available: the US must produce its own oil and thus fuel, this would drastically increase the price of fuel and also end up reducing the load factors
 - 3) Reduced Production: your competitor just launched a superior product that has resulted in you loosing production market share and thus you would need to reduce the production quantity and also the ROI to make the aircraft more economically appealing.
 - 4) Labor Unions dissolve: all labor unions are abolished by the US and you loose your entire manufacturing capability, this would affect the associated learning curves
 - 5) Airline Re-regulation: government imposes new pricing regulations to the airlines and places fix prices on certain city pairs, this would affect the airline ROI and the load factors
13. Compare the resulting CDFs and PDFs from the above scenarios to your baseline values from Step 3 (i.e., representative of today's economics) and discuss the results. Provide the assumed shape functions, the significance of the simulation, and the results in your report. Discuss why you picked the shape distribution you did to model the different scenarios.

Step 6: Specify Technology Alternatives

The objective of this step is three fold. One, identify potential technologies that may improve technical feasibility and economic viability of your vehicle. Second, establish physical compatibility rules for the different technologies identified. Third, determine the impact, both improvements and degradations, to the system of interest. For the purpose of this project, you are provided the technologies as listed in Table V. Please use the nomenclature given for the technologies when you are providing your results. *You have the freedom to add* more technologies that you may know of or that you think would be appropriate. If you do this, please see Dr. Kirby for confirmation of your choices and the impact of the ones you selected.

Next, you need to provide a compatibility matrix for the technologies. This matrix formalizes which technologies are physically compatible and as a by-product, reduces the number of alternatives to evaluate. This is important if the number of technologies considered for application is large and the combinatorial problem is out of hand. The compatibility matrix that you will use is shown in Figure 9. Note, a "1" implies the technologies are compatible and a "0" implies that a combination is NOT compatible.

Finally, once the compatibility matrix is determined, the potential system and sub-system level impacts of each technology must be established. The impact should include primary benefits and secondary degradations to the entire system to be accurately assessed. This information is formalized in a Technology Impact Matrix (TIM). The TIM is the deterministic impact estimation for a technology that has been matured to the point of full-scale and widespread application. The TIM that you will use is shown in Figure 10. Unfortunately, the technologies you were given did not have penalties. The techs were considered only from a benefit point of view.

TABLE V: SUBSONIC ALTERNATIVE TECHNOLOGIES

ID #	Technology Description	Current TRL	TRL=9 Date
1	Adaptive Performance Optim.	9	2000
2	Stitched RFI Composite on Tail Skin	4	2006
3	Stitched RFI Composite on Tail Structure	4	2006
4	Stitched RFI Composite on Wing Skin	4	2006
5	Stitched RFI Composite on Wing Structure	4	2006
6	Airframe Methods	4	2007
7	Fire Suppression	3	2007
8	Low Cost Composite Manufacturing on Tail Structure	2	2009
9	Low Cost Composite Manufacturing on Wing Structure	2	2009
10	Propulsion System Health Management	2	2009
11	Smart Nacelle-PAI	3	2009
12	Emerging Alloy Tech & Forming on Tail Skin	3	2010
13	Emerging Alloy Tech & Forming on Tail Structure	3	2010
14	Emerging Alloy Tech & Forming on Wing Skin	3	2010
15	Emerging Alloy Tech & Forming on Wing Structure	3	2010
16	Superplastic Forming on Fuselage Skin	2	2011
17	Superplastic Forming on Tail Skin	2	2011
18	Superplastic Forming On Wing Skin	2	2011
19	Russian Aluminum Lithium Fuselage Skin	4	2011
20	Adaptive Engine Control System	4	2011
21	Revolutionary Metallic Materials Systems on Fuselage Structure	2	2013
22	Revolutionary Metallic Materials Systems on Landing gear	2	2013
23	Revolutionary Metallic Materials Systems on Tail Structure	2	2013
24	Revolutionary Metallic Materials Systems on Wing Structure	2	2013
25	Composite Fuselage Shell (Fuselage Skin)	2	2013
26	Living Aircraft	2	2013
27	Active Load Alleviation on Tail	4	2013
28	Active Load Alleviation on Wing	4	2013
29	Antenna Systems	2	2014
30	Adaptive Wing Shaping	3	2014
31	Biologically Inspired Material Systems on Fuselage Structure	1	2015
32	Biologically Inspired Material Systems on Tail Structure	1	2015
33	Biologically Inspired Material Systems on Wing Structure	1	2015
34	BIOSANT on Fuselage Structure	1	2015
35	BIOSANT on Tail Structure	1	2015
36	BIOSANT on Wing Structure	1	2015

[illegible]

FIGURE 9: SUBSONIC COMPATIBILITY MATRIX

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36
Technology Impact																																				
Wing Weight (skin or structure)				-0.03	-0.03				-0.2					-0.02	-0.08										-0.15				-0.05					-0.35		-0.3
Fuselage Weight (skin or structure)																-0.12					-0.07	-0.11									-0.25			-0.21		
HT Weight (skin or structure)		-0.03	-0.13					-0.2				-0.02	-0.08											-0.15				-0.05					-0.35			-0.3
VT Weight (skin or structure)		-0.03	-0.13					-0.2				-0.02	-0.08											-0.15				-0.05				-0.35				
Cdi	-0.04										-0.01																		-0.01	-0.091						
Cdo						-0.02					-0.01																			-0.091						
Landing Gear Weight																							-0.21						-0.45							
avionics weight																																				
hydraulics weight																										-0.5										
furnishings and equipment weight								-0.02																												
VT area																															-0.15					
HT area																															-0.15					
Engine Weight										0.05																										
Fuel Consumption*																																				
RDT&E costs*																																				
O&S costs*																																				
Production costs*																																				
Utilization*																																				
Wing Area*																																				
Thrust-to-weight ratio*																																				
* Extra Impact Factor*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36

FIGURE 10: TECHNOLOGY IMPACT MATRIX

Requirements for Step 6:

1. Describe in detail why the different technologies are used for your vehicle. Provide references. Note, some technologies are duplicates with applications for different components. Please do not repeat the description.
2. Describe why each and every of the incompatible technologies are not physically compatible. Are the compatibility matrices correct? If not, explain why.
3. The values provided in the TIM assume that the technologies are *all* fully matured. What is an immature technology? Is the impact of an immature technology deterministic? If not, why isn't it and would the impact values in the TIM be different from the ones provided? If so, describe why. What is the impact a function of? Discuss and justify your answers in detail. Provide any supporting references of your answers.
4. Which research entities are working on the given technologies? What levels of research have been conducted thus far? A detailed description is required here with the addition of reference and source information. What is the rationale behind the impact values in the TIMs as applied to your vehicle? For example, why would the use of a composite wing reduce the cruise drag?
5. From the descriptions you find, estimate the potential degradations to the system from integrating the technology to the full system. For example, the infusion of a composite wing could reduce the sized vehicle wing weight by 20% and the cruise drag (due to a smoother wing surface) by 2%. Yet, the costs associated with manufacturing and maintaining this type of wing will be more than a conventional aluminum wing structure due to increased complexity and material costs. This penalty can be simulated with increased Research, Development, Testing, and Evaluation (RDT&E), production (due to more expensive materials and processes), and Operation and Support (O&S) costs due to increased maintenance times required to repair damages and so on. Provide new impact values based on your discoveries to estimate the potential impacts. You can see Dr. Kirby for a little guidance or as a sanity check for the numbers you generate.
6. Is the current level of research indicative of the TRL's provided? Justify your answers.
7. What is the significance of a TRL? Will the evaluation of the impact of the technologies on your vehicle be different if the technologies are a different TRL? If so, what must you consider?
8. Provide the original compatibility matrix and the TIM in your report.
9. Provide the modified TIM based on the results of requirement 5 above.
10. Provide a series of TCMs for each year between 2006 and 2016 in an appendix with two in the main report being for the years 2007 and 2016 (indicative of the technologies available for 2022). Call this appendix "Annual TCM". This will result in 11 TCMs that you need to supply. The TCMs should be constructed based on the compatibility rules and which technologies have reach the TRL=9 date for the TCM of that year.

Step 7: Assess Technology Alternatives

You will be evaluating your technologies deterministically for this project. To do this, you need to create RSEs for the metrics defined in Table II as a function of the "k" factors (technology impact factors) listed in the TIM. You will do the RSEs on the optimal geometric configuration you determined in Step 5. The evaluation of the technologies identified in Step 6 will be performed deterministically. Hence, a full-factorial investigation is to be performed for a given year. For example, a full-factorial evaluation for nine technologies at two levels (i.e., "on" or "off") constitutes 512 ($2^{n=9}$) combinations and with eleven technologies is 2048. The technology evaluation is to be performed by creating a metamodel of each system metric as a function of the "k" vector elements. The metamodels are second-order Response Surface Equations (RSE) of the form:

$$R = b_o + \sum_{i=1}^k b_i k_i + \sum_{i=1}^k b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} k_i k_j \quad (1)$$

where: R represents a given system metric; b_i represent regression coefficients for linear terms; b_{ii} quadratic coefficients; b_{ij} cross-product coefficients; k_i, k_j the "k" factor vector elements; and $k_i k_j$ denotes interactions between two "k" vector elements. A metamodel, RSE, is created for each system metric via a Design of

Experiments (DoE) by bounding the “k” vector element ranges as shown in Table VI. The “0” implies no change in the technical metric if the reference point is “0” and a “1” implies no change if the reference point is “1” while a negative value denotes a reduction and a positive value an increase from the baseline values you have in your FLOPS/ALCCA input files. Once Eq (1) is determined for each metric, the RSEs can be used to rapidly evaluate the impact of the various technologies based on a particular “k” vector setting in lieu of executing FLOPS/ALCCA directly.

TABLE VI: “K” FACTORS RANGES

Generic Technology Impact Vector	Minimum (%)	Maximum (%)
Wing Weight (skin or structure)	0.65	1.15
Fuselage Weight (skin or structure)	0.75	1.0
Hor Tail Weight (skin or structure)	0.6	1.0
Ver Tail Weight (skin or structure)	0.6	1.0
Cdi	0.8	1.0
Cdo	0.8	1.0
Landing Gear Weight	0.75	1.0
Avionics Weight	0.5	1.05
Hydraulics Weight	0.5	1.05
Furnishing and Equipment Weight	0.9	1.05
VT Area	Same as design space	Same as design space
HT Area	Same as design space	Same as design space
Engine Weight	0.55	1.05
Fuel Consumption*	0.8	1.01
RDT&E Costs*	-20%	+20%
O&S Costs*	-20%	+20%
Production Costs*	-20%	+20%
Utilization*	-20%	+20%
Wing Area*	Same as design space	Same as design space
Thrust-to-weight Ratio*	Same as design space	Same as design space

A full-factorial DoE should be created in JMP and the RSEs evaluated. As an example, the metric values obtained for an aircraft with aircraft morphing (T3) and IHPTET engines (T9) is depicted in Figure 11. A unique “k” vector is associated with each technology, specifically \vec{k}_3 and \vec{k}_9 . Since the impact of the various technologies is assumed to be additive, an alternative with T3 and T9 is simulated by adding each element of the vector resulting in a new vector, \vec{k}_{3+9} . The new vector is then fed into the RSEs and the metrics calculated. This is performed for every combination and every metric.

One note: the maximum number of factors that JMP can consider for a full factorial is 13.

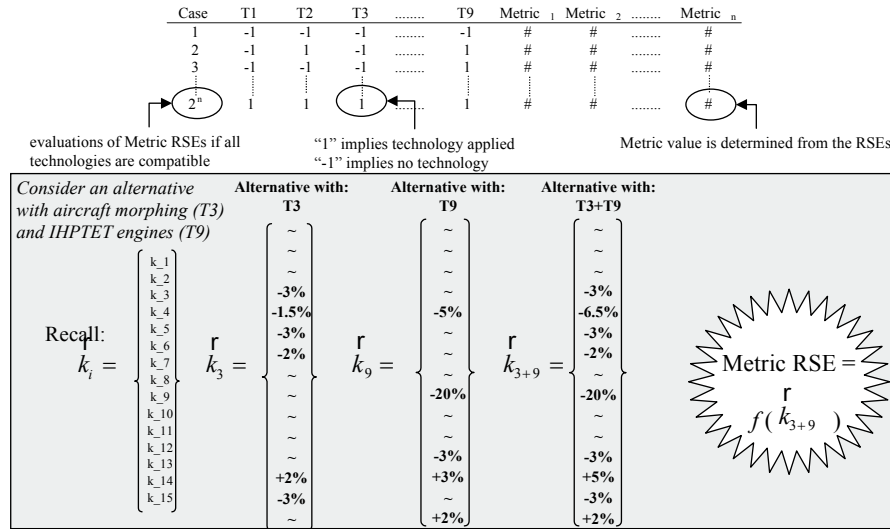


FIGURE 11: EXAMPLE TECHNOLOGY EVALUATION WITH "k" VECTORS

Requirements for Step 7:

1. Define the FLOPS/ALCCA variables, which correspond to the "k" factors given, and list the actual minimum and maximum of the variable. For example, if your baseline engine weight is 1,000 lbs for a subsonic vehicle, then the actual minimum is 500 lbs (-50%) and the maximum is 1,100 lbs (+10%).
2. How do you assess a given technology with the RSEs, i.e., how do you map the technology "k" vector to the RSEs?
3. Provide the coefficients of the system level metric RSEs, the R^2 values, a discussion of representative whole model and residual plots, and the goodness of your RSEs.
4. Provide a prediction profile for your metrics as a function of the "k" factors. See Figure 7 in Reference 5 for an example.
5. Show contour plots (again TWR versus SW) of the most significant "k" factors and how they influence the feasible and viable space. What are the active constraints for a feasible and viable space?
6. How much improvement is needed from the different technology impact factors to obtain a feasible space? To accomplish this, you can back solve your RSEs to determine the settings required to meet the metric targets. Provide 3 tables, one of the performance metrics and the required settings of the impact values to meet the metric targets independently, and one for the economics independently, and one of the settings to meet all target values concurrently. Discuss the differences of the values obtained.
7. Provide a prediction profile for your metrics as a function of technologies for each year, ie 2006 to 2016. In the main portion of the report, only put the 2007 and 2016 years. Put the remainder in another appendix called "Annual Technology Environments". You will assume for this part that all technologies are compatible for that given year. See Figure 14 in Reference 3 for an example. The techs you will assess for each years will be:

Year	Techs	Number of Techs
2006	1,2,3,4,5	5
2007	1,2,3,4,5,6,7	7
2008	1,2,3,4,5,6,7	7
now add on T1 for all, and call that your "NEW" baseline for 2009		
2009	2,3,4,5,6,7,8,9,10,11	10
now add on T6, T7 for all and call that you "NEW #2" baseline for 2010 (ie, NEW #2 should have T1,T6, T7)		
2010	2,3,4,5,8,9,10,11,12,13,14,15	12
now merge the following technologies: T2 and T3 into T2-3 T4 and T5 into T4-5 T12 and T13 into T12-13 T45 and T15 into T14-15		
2011	T2-3,T4-5,T12-13,T14-15,8,9,10,11,16,17,18,19,20	12
2012	Same as 2011	
now add on T10, T11, T20, T27, and T28 for all, and call that your "NEW #3" baseline for 2013 (ie, NEW #3 should have T1,T6, T7, T10, T11, T27, T28)		
2013	T2-3,T4-5,8,9,16,17,18,21,22,23,24,25,26	13
now add on T26 for all, and call that your "NEW #4" baseline for 2014 (ie, NEW #4 should have T1,T6, T7, T10, T11, T26, T27, T28)		
2014	T2-3,T4-5,8,9,17,18,21,22,23,24,25, 29, 30	13
now add on T29 for all, and call that your "NEW #5" baseline for 2014 (ie, NEW #4 should have T1,T6, T7, T10, T11, T26, T27, T28, T29)		
2015	25, 30, 31,32, 33,34,35,36	8
2016	skip this one since it is the same as 2015	

8. Why did I pick the above technology combinations for a given year? Please rationalize and discuss other ways of assessing the technologies.
9. Provide the shell scripts you used to run FLOPS/ALCCA and extraction of the data as an appendix called "Scripts".
10. Why are you evaluating the impact of the technologies on a fixed vehicle? Provide some rationale as to how you could investigate a technology space and a geometric design space concurrently?
11. How would you evaluate the impact of technologies in a probabilistic manner?
12. In reality, are the technologies additive, where additive implies that the technology impacts are independent of each other. Discuss why or why not. If not, describe how you might evaluate a technology mix that *is not* additive.
13. Create Decision Matrices for each year between 2006 and 2016 where the rows are the technology alternatives denoted as T1+T3+T32 or T5+T12+T19 and so on and the columns are the metrics. Put 2007 and 2016 in the main report and the others in an appendix entitled "Annual Decision Matrices".
14. If you were assessing your technologies in a probabilistic manner, how would you populate the matrix so that you would be comparing apples and apples?

Step 8: Select best family of alternatives

This final step in the TIES method is where you select the “best” mix of technologies to satisfy the system level metrics. For any multi-attribute, -constraint, or -objective problem, the selection of the “best” family of alternatives is inherently subjective and no single answer will fulfill all requirements. Four approaches are proposed to account for the subjectivity of the problem:

1. Multi-Attribute Decision-Making (MADM) techniques in the form of TOPSIS
2. Technology Frontiers: Performance and Economic Effectiveness
 3. Technology Sensitivities: One-to-one technology comparison
 4. Genetic Algorithms (GA)

Look at Reference 2 for a detailed description of how to do this aspect along with TIES for Dummies. One minor change from the reference is the change of the selection technique of “Resource Allocation” to “Technology Sensitivities” for clarity.

You will be provided spreadsheets that will implement TOPSIS and the Frontiers. You may need to modify the spreadsheet for your particular problem. You will need to create a spreadsheet to calculate the sensitivities.

Requirements for Step 8:

1. Describe how TOPSIS works.
2. Consider at least 10 different weighting scenarios for TOPSIS and provide the top 10 technology mixes that result for each year, again with 2007 and 2016 in the main report and the other in an Appendix entitled “Annual TOPSIS Scenarios”. Also, provide the weighting scenarios considered in tabular and graphical form. Discuss the significance of the results. Do any mix of technologies tend to appear in most of the different weighting scenarios? If so, discuss why.
3. For the technology frontiers, provide the equations used to calculate the performance and economic frontiers and discuss what frontiers are. Establish threshold limits and discuss how they were established.
4. Provide plots of PE versus EE for each year with 2007 and 2016 in the main report and the others in an appendix entitled “Annual Technology Frontiers”. The technology combinations should be grouped by how many technologies were on the vehicle at a given time, look at Figure 9 in Reference 2. Put the threshold limits on the plots and identify the feasible technology space and the “Ideal” and “Best Compromise” solutions, identify a few combinations as being compromises. If you do not have a clue how to do this in Excel, see Dr. Kirby for guidance.
5. Describe the basic principles of how Genetic Algorithms work.
6. Define the metrics which were the most severe from your feasibility study in Step 5. Based on these metrics consider 5 different Objective Functions and 5 different weighting scenarios for each Objective Function (25 total assessments) that will be used in a GA assessment to determine which technology sets improve these responses. Investigate the best technology sets that result from this investigation and determine which technology sets occur more often. From the GA assessment which technology combination is the best for each Objective Function and weighting scenario? What individual technologies appear in the resulting 25 top technology combinations? Comment on why these superior technologies are superior. If you were to pick one technology combination as the best which one would it be and why?
7. Compare the best technology from the GA approach to the results you obtained from the TOPSIS approach and the frontier approach. Are the best technology sets from the different selection approaches the same? Discuss in detail these results of the different selection approaches. Which is the best technology set and rationalize your decision.
8. For technology sensitivities, compare the influence of each individual technology to the baseline metrics you obtained from your geometric optimal design, i.e., what percent change from the baseline metrics do the technologies have on your baseline vehicle. Provide a plot for each metric. See Figure 16 in Reference 3 for an example.

9. Would the influence of the individual technologies (wrt technology sensitivities) change if you were assessing the impact probabilistically? If so, why? Qualitatively discuss what you think might happen.
10. If a particular technology can help a metric, does it have a negative influence on other metrics? Discuss how each technology influences the metrics, whether positive or negative.
11. If you were a program manager, which technologies would you invest development funds and why? Provide a summary of which technology combinations were superior from the different selection approaches to justify your decision. Provide tabular data, comparisons, or plots to justify.

Closing the Loop: Reinvestigate the Design Space with Technologies

The design of any complex, multi-attribute system is highly subjective, especially in the early phases of the development. Thus, the selection of a single concept alternative is highly dependent on the decision-maker's judgement and relative importance of the evaluation criteria. Because of this, the family of alternative concepts that have been identified through the execution of TIES should be carried through the design process to retain design freedom as long as possible (think of the cost-knowledge-freedom curve). This process entails a re-investigation of the design space with the various technology alternatives that were deemed as the most significant from the selection step results. Subsequently, Steps 4 and 5 are repeated to determine if a different geometry will further increase the feasibility of the system for the family of technology alternatives. Thus, iteration is required within the TIES method. However, the iteration is rapid once the initial method is established.

Requirements for Closure:

1. Identify the best two technology combinations from Step 8, requirement 7 and provide a table of the technology combinations only for the 2016 year technologies. Provide a new alternative description scheme, i.e., for combo with T2+T5+T26, I will call that Alternative #1 and combo with T6+T17+T21, I will call that Alternative #2, and so on.
2. Provide a table of the combined tech vector values (rows) against the technology combinations (columns).
3. Modify your baseline FLOPS/ALCCA file to reflect each one of the alternatives that you established. Thus, you will have a baseline FLOPS/ALCCA file for Alt #1 and one for Alt #2.
4. Provide a table of the comparisons of the metrics for the new alternative metrics to the baseline as you did with the optimized baseline, i.e., metric values and percent differences.
5. Create RSEs of the metrics for each vehicle based on fixed "k" factors with the design variables in Table III. Check the goodness of your fit as you did in Step 4 but do not repeat the random cases or the viability assessments from Step 5.
6. Extract the equations and repeat the Monte Carlo Simulation of the design space. Extract the percentiles again and compare these new CDF's for each Alternative and metric to the original CDFs you generated in Step 5. Provide the CDF's.
7. Discuss the differences between the CDF's you obtained.
8. Provide a summary or a conclusion section to wrap up all of your ideas and efforts.

Final Requirements

1. Discuss what you have learned and what is the value added to your knowledge through the implementation of the two projects.
2. What difficulties did you encounter in the two projects?
3. What difficulties did you encounter with FLOPS/ALCCA?
4. What would you suggest for future design projects?
5. Could you use the TIES method to design or evaluate other complex systems?
6. What do you feel is missing in the TIES method?
7. What other valuable feedback can you provide for future students?

Appendix A: JPDM Code and Application

JPDM computer program implementation for PAV Application problem

After the Data files are obtained, three simple steps should be taken to run the EDF model of JPDM.

1. Place these Data files in the same folder where the other MATLAB files are. The directory tree of the JPDM computer program is presented in the figure below.



2. Change the values of some parameters in the *inputsEDF.m* file for your specific problem. For example,


```

maxvalue = [130 79 3.5];
minvalue = [0 0 0];
crplots = [1 2];
name(1) = {'DOC[$/hr]'};
name(2) = {'NOISE[db]'};

```
3. Run *JPDM.m*. Finally you will get the results including the probability table and corresponding graphs (Table 1 and Figure 4). For more details please refer to the Appendix D in reference 8.

MATLAB Scripts for JPDM PAV problemJPDM.m

The first line in MATLAB® specifies the file name:

```
% JPDM.m
```

Initiation: erase memory

```
clear all
```

set clock to determine length of run for time comparisons

```
ff = clock;
```

Default Values

for plotting only

```
crplots = [0 0];
```

```
t = 1;
```

```
sp = 0;
```

```
aalow = [0 0 0 0];
```

```
aahigh = [0 0 0 0];
```

calls the parameters specified in inputsEDF.m into the memory

```
inputsEDF
```

```
%inputsJPM
```

determine the number of criteria (fom = figure of merit) from the number of maximum values specified in inputs.m

```
nfom = length(maxvalue);
```

determine which method: EDF or JPM

```
if method == 1
```

determine number of alternatives from the number of specified distributions for the first criterion in inputsJPM.m

```
points = length(distribution(:,1));
```

```
JPM
```

```
elseif method == 2
```

determine number of alternatives from the number of entries in the variable that specifies the size of the data sample in Data1, Data2, ..., DataM

```
points = length(1);
```

```
EDF
```

```
end
```


inputsEDF.m

```
% inputsEDF.m
```

```
specify method: JPM = 1, EDF = 2
```

```
method = 2;
```

```
definition of area of interest by assigning limits for each criterion
```

```
maxvalue = [130 79 3.5];
```

```
minvalue = [0 0 0];
```

```
assigning number of steps taken for plotting; criteria in columns, alternatives in rows; different numbers of steps for different alternatives are possible
```

```
nstep = [100 100 100; 100 100 100; 100 100 100];
```

```
defining length of data matrixes; 1 describes how many samples were collected for each alternative (number can vary with alternative)
```

```
l = [10000; 10000; 10000];
```

```
assignment of which criteria are plotted against each other (here Criterion 1 against Criterion 2); can be expanded to many more rows, limited to two columns
```

```
crplots = [1 2];
```

```
assigning a range for each criterion that the joint distribution is conditioned on (here 1 and 2); criteria are in columns, minimum in first row, maximum in second row; assigning ranges to criteria identified for plotting in crplots has no effect on that particular plot.
```

```
condrange = [-100 -100; 100 100];
```

```
plotting identifier for joint distributions in 2-D (density), 3-D (density), and cumulative probability (2-D); y = yes, n = no
```

```
probplot2D = 'y';
```

```
probplot3D = 'n';
```

```
cumplot = 'n';
```

```
identify values of joint density to be plotted in 2-D ('cuts' through joint probability hump); major parameter for creating desired plots
```

```
cp = (0.00005:0.0003:0.05);
```

```
identify values of joint cumulative probability to be plotted in 2-D
```

```
cc = [0,0.1,.2,.3,.4,.5,.6,.7,.8,.9];
```

```
identify names for criteria to be plotted
```

```
name(1) = {'DOC[$/hr]'};
```

```
name(2) = {'NOISE[db]'};
```

```
identify colors for each alternative distribution (refer to MATLAB manual for color codes)
```

```
contourcolors = ['k'; 'b'; 'r'];
```

EDF.m

```
% EDF.m
dat = NaN * ones(nfom,max(l),points);
fid(1) = fopen('Data1','r');
fid(2) = fopen('Data2','r');
fid(3) = fopen('Data3','r');
fid(4) = fopen('Data4','r');
fid(5) = fopen('Data5','r');
fid(6) = fopen('Data6','r');
fid(7) = fopen('Data7','r');
fid(8) = fopen('Data8','r');
fid(9) = fopen('Data9','r');
fid(10) = fopen('Data10','r');
fid(11) = fopen('Data11','r');
for n = 1:points
    dat(:,n) = fscanf(fid(n),'%g',[nfom l(n)]);
    data(:,n) = dat(:,n)';
end
status = fclose('all');
for n = 1:points
    xmin(n,:) = min(data(:,n),[],1);
    xmax(n,:) = max(data(:,n),[],1);
    lower(n,:) = max(xmin(n,:),minvalue);
    upper(n,:) = min(xmax(n,:),maxvalue);
    fidd = fopen('passEDF','w');
    if n == 1
        !copy Data1 Data
    elseif n == 2
        !copy Data2 Data
    elseif n == 3
        !copy Data3 Data
    elseif n == 4
        !copy Data4 Data
    elseif n == 5
        !copy Data5 Data
    elseif n == 6
        !copy Data6 Data
    elseif n == 7
        !copy Data7 Data
    elseif n == 8
        !copy Data8 Data
    elseif n == 9
        !copy Data9 Data
    elseif n == 10
```

```

!copy Data10 Data
elseif n == 11
!copy Data11 Data
end
if nfom == 2
step(n,:) = (xmax(n,:)-xmin(n,:))./nstep(n,:);
fprintf(fidd,'%g\n',l(n),xmin(n,:),xmax(n,:),step(n,:),lower(n,:),upper(n,:));
status = fclose(fidd);
!EDF2.exe
x(n,:) = xmin(n,1) + step(n,1)/2:step(n,1):xmax(n,1);
y(n,:) = xmin(n,2) + step(n,2)/2:step(n,2):xmax(n,2);
fidd = fopen('passback','r');
i = fscanf(fidd,'%g',[1 1]);
j = fscanf(fidd,'%g',[1 1]);
count = fscanf(fidd,'%g',[i j]);
C(n) = fscanf(fidd,'%g',[1 1]);
countv(n,:) = fscanf(fidd,'%g',[1 nfom]);
status = fclose(fidd);
prob(:,n) = count(2:i,2:j)/l(n);
prob(1,:,n) = (count(1,2:j) + count(2,2:j))/l(n);
prob(:,1,n) = (count(2:i,1) + count(2:i,2))/l(n);
plotx = 1;
ploty = 2;
if n == points
cd plot.files
if probplot2D == 'y'
contourplot
end
if probplot3D == 'y'
surfplot
end
if cumplot == 'y'
cumprobplot
end
cd ..
end
elseif nfom == 3
fprintf(fidd,'%g\n',l(n),lower(n,:),upper(n,:));
status = fclose(fidd);
!EDF3.exe
fidd = fopen('passback','r');
C(n) = fscanf(fidd,'%g',[1 1]);
countv(n,:) = fscanf(fidd,'%g',[1 nfom]);
status = fclose(fidd);
elseif nfom == 4
fprintf(fidd,'%g\n',l(n),lower(n,:),upper(n,:));

```

```
status = fclose(fidd);
!EDF4.exe
fidd = fopen('passback','r');
C(n) = fscanf(fidd,'%g',[1 1]);
countv(n,:) = fscanf(fidd,'%g',[1 nfom]);
status = fclose(fidd);
elseif nfom == 5
    fprintf(fidd,'%g\n',l(n),lower(n,:),upper(n,:));
    status = fclose(fidd);
    !EDF5.exe
    fidd = fopen('passback','r');
    C(n) = fscanf(fidd,'%g',[1 1]);
    countv(n,:) = fscanf(fidd,'%g',[1 nfom]);
    status = fclose(fidd);
end
end
if sum(sum(crplots)) > 3
    if nfom == 3
        elseif nfom == 4
            crosspl4
        elseif nfom == 5
            end
            ConditionalProbability(3:points+2,1) = [1:points]';
            for m = 1:length(crplots(:,1))
                ConditionalProbability(1:2,m+1) = [crplots(m,1);crplots(m,2)];
                ConditionalProbability(3:points+2,m+1) = ccond(:,m)./cl(:,m);
            end
            ConditionalProbability
        end
        cumulative = C'./l;
        probtable = zeros(points+1,nfom+2);
        probtable(2:points+1,1) = transpose(1:points);
        probtable(1,2:nfom+2) = (0:nfom);
        probtable(2:points+1,2) = cumulative;
        for n = 1:points
            probtable(n+1,3:nfom+2) = countv(n,:)/l(n);
        end
        probtable
        if sum(sum(crplots)) > 3
            cl
        end
        ee = etime(clock,ff);
```

EDF2.exe

```
program EDF2
  implicit none
  real x, y, xmin, xmax, ymin, ymax, stepx
  real minx, maxx, miny, maxy, data(15000,2)
  real count(1001,1001), stepy, epsx, epsy
  integer k, i, j, l, s, t, C, CX, CY
  C = 0
  CX = 0
  CY = 0
  open (8, FILE = 'passEDF', status = 'old')
  read (8, *) l, minx, miny, maxx, maxy, stepx
  read (8, *) stepy, xmin, ymin, xmax, ymax
  open (9, FILE = 'Data', status = 'old')
  epsx = stepx/100.
  epsy = stepy/100.
  do 10 k = 1,l
    read (9, *) data(k,1), data(k,2)
    j = 0
    do 20 x = minx,maxx+epsx,stepx
      i = 0
      j = j + 1
      do 30 y = miny,maxy+epsy,stepy
        i = i + 1
        if (data(k,1) .gt. x - stepx) then
          if (data(k,1) .le. x) then
            if (data(k,2) .gt. y - stepy) then
              if (data(k,2) .le. y) then
                count(i,j) = count(i,j) + 1
              endif
            endif
          endif
        endif
      enddo
    enddo
    continue
  30  continue
  20  continue
  if (data(k,1) .ge. xmin) then
    if (data(k,1) .le. xmax) then
      if (data(k,2) .ge. ymin) then
        if (data(k,2) .le. ymax) then
          C = C + 1
        endif
      endif
    endif
  endif
  if (data(k,1) .ge. xmin) then
    if (data(k,1) .le. xmax) then
      CX = CX + 1
    endif
  endif
  if (data(k,2) .ge. ymin) then
    if (data(k,2) .le. ymax) then
      CY = CY + 1
    endif
  endif
enddo
```

```

        endif
    endif
10    continue
    open (10, FILE = 'passback')
    write (10, *) i, j
    do 40 s = 1,j
        do 50 t = 1,i
            write (10, *) count(t,s)
50        continue
40    continue
    write (10, *) C
    write (10, *) CX
    write (10, *) CY
    endfile (10)
    close (10)
    close (9)
    close(8)
end

```

EDF5.exe

```

program EDF5
    implicit none
    real min(5), max(5), data(15000,5)
    integer k, l, s, D, C(5)
    D = 0
    do 5 s =1,5
        C(s) = 0
5    continue
    open (8, FILE = 'passEDF', status = 'old')
    read (8, *) l, (min(s), s=1,5), (max(s), s=1,5)
    open (9, FILE = 'Data', status = 'old')
    do 10 k = 1,l
        read (9, *) (data(k,s), s=1,5)
        if (data(k,1).ge.min(1) .and. data(k,1).le.max(1)) then
        if (data(k,2).ge.min(2) .and. data(k,2).le.max(2)) then
        if (data(k,3).ge.min(3) .and. data(k,3).le.max(3)) then
        if (data(k,4).ge.min(4) .and. data(k,4).le.max(4)) then
        if (data(k,5).ge.min(5) .and. data(k,5).le.max(5)) then
            D=D+1
        endif
        endif
        endif
        endif
        endif
        do 20 s = 1,5
            if(data(k,s).ge.min(s) .and. data(k,s).le.max(s))then
                C(s)=C(s)+1
            endif
20        continue
10    continue

```

```

        open (10, FILE = 'passbackEDF')
        write (10, *) D
        do 40 s = 1,5
            write (10, *) C(s)
40    continue
        endfile (10)
        close (10)
        close (9)
        close(8)

    end

```

contourplot.m

Objective: Creates a contour plot of the joint probability function for two criteria.

```

% contourplot.m %
figure

hold figure to overlay area of interest, distribution, and limits; plot is created for two criteria at a time:
plotx and ploty, assigned in EDF.m or JPM.m
hold

create grid over area of interest, identified by green "dots" plotted at grid points
[xm,ym] = meshgrid(max(min(min(x)),minvalue(plotx))+step(1,plotx)
/2:step(1,plotx):min(max(max(x)),maxvalue(plotx))-
step(1,plotx)/2,max(min(min(y))+step(1,ploty)/2,
minvalue(ploty)):step(1,ploty):min(max(max(y)),
maxvalue(ploty))-step(1,ploty)/2);

plot(xm,ym,'g.');
```

plot distribution for each alternative

```

for n = 1:points
    plot contours of constant joint probability (prob) over the first (xm) and second (ym) criterion. cp is
    vector with probability values to be plotted
    [Cont,H] = contour(x(n,:),y(n,:),prob(:,:,n),cp,'-');
    set(H,'Color',contourcolors(n,:))
end

```

plot limits of area of interest

assigns values which the limits are plotted against

```

ycp = min(min(x)):step(1,plotx):max(max(x));
xcp = min(min(y)):step(1,ploty):max(max(y));

```

identifies whether minimum limit for first criterion (x) needs to be plotted

```

if minvalue(plotx) > min(min(x))
    assigns limit values to vector
    lo = ones(1,length(xcp))*minvalue(plotx);
    plots line by plotting constant x-value against changing y-values (x-limit)
    plot(lo,xcp)

```

```

clear lo
end

identifies whether minimum limit for second criterion (y) needs to be plotted
if minvalue(ploty) > min(min(y))
assigns limit values to vector
    lo = ones(1,length(ycp))*minvalue(ploty);
plots line by plotting constant y-value against changing x-values (y-limit)
    plot(ycp,lo)
    clear lo
end

identifies whether maximum limit for first criterion (x) needs to be plotted
if maxvalue(plotx) < max(max(x))
assigns limit values to vector
    lo = ones(1,length(xcp))*maxvalue(plotx);
plots line by plotting constant x-value against changing y-values (x-limit)
    plot(lo,xcp)
    clear lo
end

identifies whether maximum limit for second criterion (y) needs to be plotted
if maxvalue(ploty) < max(max(y))
assigns limit values to vector
    lo = ones(1,length(ycp))*maxvalue(ploty);
plots line by plotting constant y-value against changing x-values (y-limit)
    plot(ycp,lo)
    clear lo
end

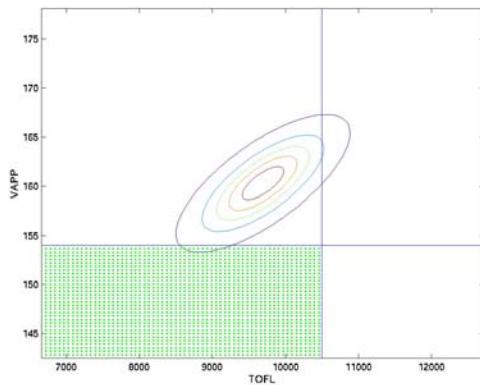
focus plot on area just plotted or on area specified in inputs.m
if sum(aalow) == 0
    axis tight
else
    axis([aalow(plotx) aahigh(plotx) aalow(ploty) aahigh(ploty)])
end

label x- and y-axes
xlabel(name(plotx));
ylabel(name(ploty));
save plot in file named 'prob2D.jpg'
print -djpeg95 prob2D.jpg
hold

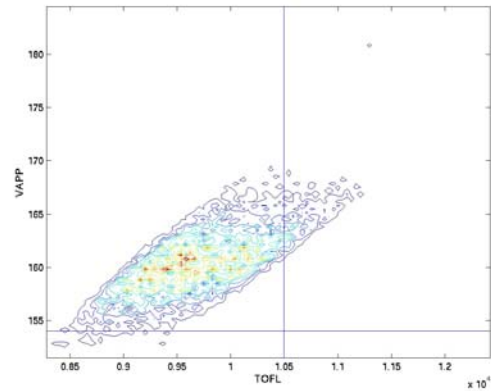
```

The contour plot displays lines of constant probability that indicate in two dimensions in which region the joint probability distribution resides. The plot also indicates the area of interest, i.e. values that satisfy both figures of merit. Hence, the plot symbolizes the probability of satisfying the FOMs by the area within probability lines, which fall within the area of interest. If the lines of constant probability fall well within the area of interest, the probability is large. If they fall outside, the probability is small.

The plot is further an excellent visual comparison of the different products in the study. The lines of constant probability of all products are overlaid and can be compared by inspection as to how well they satisfy the individual or joint figures of merit.



Contour plot from JPM method



Contour plot from EDF method

surfplot.m

Objective: Creates a surface (JPM) or column (EDF) plot, of the joint probability function for two criteria.

```
% surfplot.m %
figure

identify whether all cases are supposed to be overlaid.
if sp == 0
    plots are created for each case and overlaid.
    for n = 1:points
        for method 2 (EDF) a column plot is more desirable.
        if method == 2
            for the column plot the order of columns needs to be reversed.
            tprob(:, :, n) = fliplr(prob(:, :, n));
            print 3D column plot. Note: the function 'bar3' does not label the x-axis in the current version.
            Mathworks promised to change that in one of the next versions of Matlab.
            graph = bar3(y(n, :), tprob(:, :, n));
            change view angle of the plot.
            view(155, 20);
        else
            create continuous surface plot for joint density from JPM method.
            graph = surf(x(n, :), y(n, :), prob(:, :, n));
            change view angle of the plot.
            view(-15, 30);
        end
        change line color to light gray for better printing in black-and-white.
        set(graph, 'EdgeColor', [0.6 0.6 0.6]);
        hold on
    end
else
    only one plot is created. sp is identifier as to which one of the products plotted.
    if method == 2
```

```

tprob = fliplr(prob(:, :, sp));
graph = bar3(y(sp, :), tprob);
view(155, 20);
else
    graph = surf(x(sp, :), y(sp, :), prob(:, :, sp));
    view(-15, 30);
end
set(graph, 'EdgeColor', [0.6 0.6 0.6]);
hold on to existing plot.
hold on
end

```

focus plot on area just plotted

axis tight

label x- and y- and z-axes

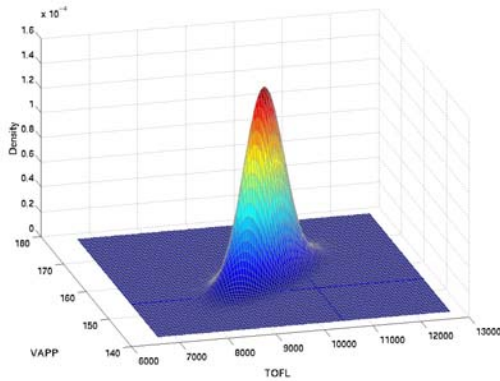
xlabel(name(plotx));

ylabel(name(ploty));

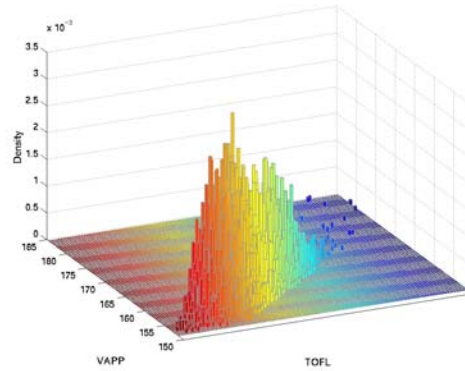
zlabel('Density');

save plot in file named 'prob2D.jpg'

print -djpeg95 prob3D.jpg



SURFACE PLOT FROM JPM METHOD



COLUMN PLOT FROM EDF METHOD

Note: the function 'bar3' does not label the x-axis in the current version. Mathworks promised to change that in one of the next versions of Matlab.

cumprobplot.m

```
% cumprobplot.m %
```

set step size for both FOMs to one if Method 2 (EDF) was used to calculate prob. EDF counts occurrences of data, i.e. mass. Thus, the cumulative probability, calculated by summation not integration of prob, does not need to be normalized by the step size.

```
if method == 2
    step = ones(points,nfom);
end
```

determine size of prob.

```
[ey,ex] = size(prob(:, :, 1));
```

```
for n = 1:points
```

reduce size of vector for second criterion. This reduces the runtime for a fine grid. The cumulative probability plot can afford to have a larger grid than the joint density plot.

```
    for i = 1:round(t):ey
        kt = 1+(i-1)/round(t);
```

reduce size of vector for first criterion.

```
        for j = 1:round(t):ex
            lt = 1+(j-1)/round(t);
```

sum/numerically integrate probability values over area of interest.

```
        if direction(plotx) == 'l'
            if direction(ploty) == 'l'
                cmp(kt,lt,n) = sum(sum(prob(i:ey,j:ex,n)));
            elseif direction(ploty) == 's'
                cmp(kt,lt,n) = sum(sum(prob(1:i,j:ex,n)));
            end
        elseif direction(plotx) == 's'
            if direction(ploty) == 'l'
                cmp(kt,lt,n) = sum(sum(prob(i:ey,1:j,n)));
            elseif direction(ploty) == 's'
                cmp(kt,lt,n) = sum(sum(prob(1:i,1:j,n)));
            end
        end
    end
end
```

```
    end
    cump(:, :, n) = cmp(:, :, n)*prod(step(n, :));
```

```
end
```

```
figure
```

```
for n = 1:points
```

plot contours of constant cumulative probability (cump) over the first (xc) and second (yc) FOM. cc is vector with probability values for plot.

```
    [Cont,H] = contour(x(n,:),y(n,:),cump(:, :, n),cc, '-');
    set(H, 'Color', contourcolors(n, :))
    clabel(Cont,H, 'fontsize', 8, 'color', contourcolors(n, :), 'labelspacing',
        1000);
```

hold on to plot in order to overlay all products that need to be compared.

```
    hold on
```

```
end
```

plot crossbar for values of interest.

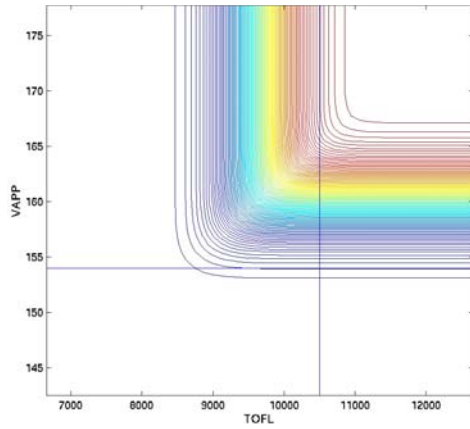
```

if maxvalue(plotx) > xmax(n,plotx)
    cx = ones(1,length(y(n,:)))*minvalue(plotx);
    if maxvalue(ploty) > xmax(n,ploty)
        cy = ones(1,length(x(n,:)))*minvalue(ploty);
    elseif minvalue(ploty) < xmin(n,ploty)
        cy = ones(1,length(x(n,:)))*maxvalue(ploty);
    end
elseif minvalue(plotx) < xmin(n,plotx)
    cx = ones(1,length(y(n,:)))*maxvalue(plotx);
    if maxvalue(ploty) > xmax(n,ploty)
        cy = ones(1,length(x(n,:)))*minvalue(ploty);
    elseif minvalue(ploty) < xmin(n,ploty)
        cy = ones(1,length(x(n,:)))*maxvalue(ploty);
    end
end
plot(x,cy)
plot(cx,y)

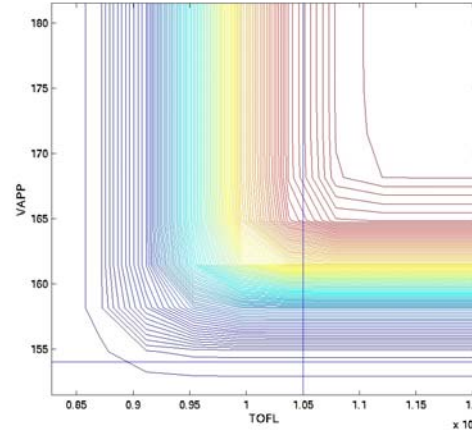
focus plot on area just plotted or on area specified in inputs.m
if sum(aalow) == 0
    axis tight
else
axis([aalow(plotx) aahigh(plotx) aalow(ploty) aahigh(ploty)])
end
label x- and y-axes.
xlabel(name(plotx));
ylabel(name(ploty));
save plot in file named 'cum2D.jpg'.
print -djpeg95 cum2D.jpg

```

The cumulative probability plot displays lines of constant cumulative probability. The cumulative probability captures all values in the area of interest already. Hence, in this plot there is no area but a point of interest, indicated by the cross mark. In addition to reading the probability value off the lines at the mark, the plot facilitates two major investigations. First, a comparison of products that uses an overlay of all products' cumulative probability plots, indicating which product yields the highest probability. Second and more importantly, it can be used for 'What-if-studies'. For example, the plot would immediately tell what the new probability value is, if the values of interest were to change. It can demonstrate directly how one product that may not have had a high probability for the first set of values performs better for the second, while another one performs conversely. The plot facilitates another type of 'What-if-studies': "How much can I gain in one criterion, if I was able to relax the other?" These trade-offs can be done in the knees of the lines. While holding the probability constant, i.e. at a constant chance of achieving the criterion values, one criterion can be traded against the other. These trades then can be done at different probability levels, thus indicating the change in trade with changing probability.



CUMULATIVE PROBABILITY PLOT (JPM METHOD)



CUMULATIVE PROBABILITY PLOT (EDF METHOD)

Appendix B: Representative TIES Implementation

Please see the electronic file entitled “150 Pax Report Final.doc” or “150 Pax Report Final.pdf” on the CD.

Appendix C: TIES for Dummies Tutorial

Please see the electronic file entitled “TIES_for_Dummies_JMP_Ver4.pdf” in the New_TIES_Demo” directory of the CD.

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